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ABSTRACT

This concept module on radiation is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. This module addresses mainly the topic of electromagnetic radiation. Included with the concept module are twenty-two application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratory exercise. Laboratory modules included are Inverse Square Law: Spreading of Light; The Optical Spectrum: Light Sources; Lasers; Stroboscopes: Pulses of Light; Optical Filters: Absorption of Light; Specular and Diffuse Reflection of Light: Image Formation with Mirrors; Prisms: Refraction and Dispersion of Light; Lenses: Focusing and Spreading of Light: Interference: Testing Flat Surfaces; Diffraction Grating: Measuring the Wavelengths of Light; Polarization: Glare Reduction; Holography: Three Dimensional Photography; Spectroscopy: Light Analysis; Infrared Radiation Thermometers; Illumination: Single Lens Reflex Camera: Geiger Counters; Penetrating Power of Alpha and Beta Radiation: Radioactivity; and Absorption of Gamma Radiation. (LRA)

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UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 13-0

ED190761

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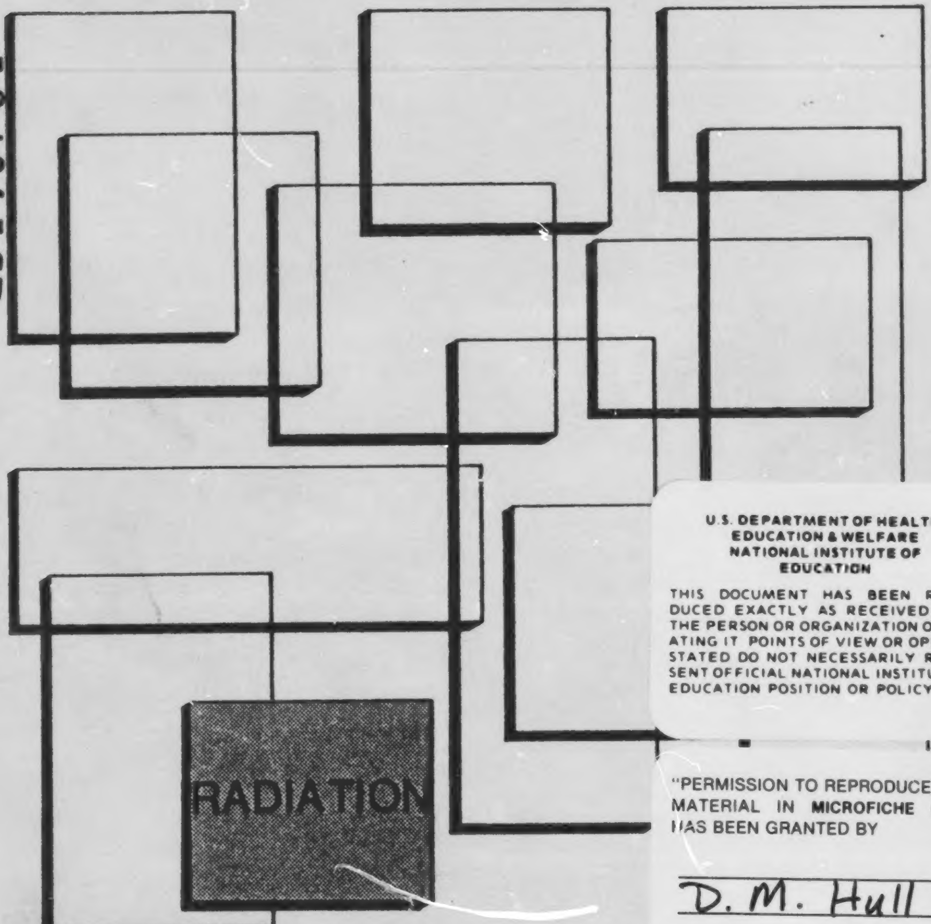

RADIATION

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INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians shouid achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet specific needs of students in a specific technology.

STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems force and torque cause motion of mass.
- In fluidal systems pressure difference causes motion of fluids.
- In electrical systems potential difference causes motion of mass.
- In thermal systems temperature difference causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

COMPONENTS OF UTC

UTC incorporates three types of modules.

CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5E5 "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

INTRODUCTION

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

PREREQUISITES

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

OBJECTIVES

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

DISCUSSION

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

LABORATORY (called DEMONSTRATIONS in the Concept Modules)

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

SELF CHECK

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

REFERENCES

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS

13-0 Radiation
13L1 Inverse Square Law — Spreading of Light
13L2 The Optical Spectrum
13L3 Light Sources
13L4 Lasers
13L5 Stroboscopes — Light Pulses
13L6 Optical Filters — Absorption of Light
13L7 Specular and Diffuse Reflection of Light
13L8 Image Formation with Mirrors
13L9 Prisms — Refraction and Dispersion of Light
13L10 Lenses — Focusing and Spreading of Light
13L11 Interference — Testing Flat Surfaces
13L12 Diffraction Grating — Measuring the Wavelengths of Light
13L13 Polarization — Glare Reduction
13L14 Holography — Three Dimensional Photography
13L15 Spectroscopy — Light Analysis
13L16 Infrared Radiation Thermometers
13L17 Illumination
13L18 Single Lens Reflex Camera
13N1 Geiger Counter
13N2 Penetrating Power of Alpha and Beta Radiation
13N3 Radioactivity
13N4 Absorption of Gamma Radiation

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INTRODUCTION

Radiation is the process by which energy moves away from a source in a straight line. Sound waves, light waves, and alpha and beta rays are examples of radiation. Although these examples represent three distinct classes of radiation, each example moves energy radially away from some source, and all have common characteristics.

Sound waves are pressure variations and require a material medium for transmission. They are discussed in Concept Module 11-0, "Vibrations and Waves," and will be mentioned here only briefly. This module addresses mainly the topic of electromagnetic (EM) radiation — sometimes called "radiant energy." In this type of radiation, energy is transmitted by variations in electric and magnetic fields. Radiant energy includes gamma rays, x-rays, ultraviolet, visible, infrared, microwaves, radar, television, and radio waves. It is the basis of modern communication, of solar energy, and of sight itself. Since EM radiation is so important in our lives, most of this module will deal with this type of radiation. Alpha and beta (nuclear) particles also will be discussed briefly as examples of particle radiation in which energy is transmitted as kinetic energy of particles.

PREREQUISITES

Student should have completed Concept Module 11-0, "Vibrations and Waves"; and Application Modules IE3, "Electric Forces and Fields," and IE4, "Magnetic Forces and Fields."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Describe in one or two sentences the basic properties of each of the following types of radiation:

    Sound.
    Light.
    Alpha and beta particles.

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- Define electromagnetic radiation (radiant energy), and describe a simple experiment that illustrates how electromagnetic radiation can be created.

- List the frequencies in the electromagnetic spectrum from long wavelength EM waves of a.c. power (60 hertz) to gamma rays (10^{22} hertz), including each major part — radio, FM, television, radar, microwave, infrared, visible, ultraviolet, x-ray, and gamma ray.

- Given the equation $v = \lambda f$ — relating wave speed, wavelength, and frequency — determine the radiation frequency for any part of the electromagnetic spectrum.

- Given the equation $E = hf$ or $E = h\,c/\lambda$, determine the energy of different waves in the EM spectrum.

- Describe qualitatively the nature of an electromagnetic wave in terms of electric and magnetic fields; state what is always required to generate an EM wave; and explain how EM waves are propagated through empty space without benefit of an elastic medium.

- Describe a photon, and explain why both wave and particle-like (photon) phenomena are required to describe interaction of EM radiation with matter. Give examples in which the wave character is most useful in describing EM radiation and in which the photon character is most useful.

- Explain what is meant by the inverse-square law and how this law is used to describe the fall-off of EM radiation propagating from a small source.

- Define polarization, and explain what is meant by polarized EM radiation — in particular, polarized light.

- Define visible radiation, and determine its limits numerically in terms of wavelength, frequency, and energy.

- Describe the reflection and refraction of EM radiation — especially light — and set up an experiment to verify the two laws.

- Differentiate between alpha and beta radiation and gamma radiation.

- Briefly explain each of the three parts in the symbol $_{92}U^{238}$.

- Given the appropriate equipment, illustrate and verify the inverse-square law of EM radiation in the visible region.

- Given the appropriate equipment, produce and detect polarized light in the microwave region.

Radiation is the movement of energy along a straight line away from an energy source. The direction of energy flow may be changed after the energy leaves the source; but unless the direction is changed, energy will continue to move radially away from the source. There are three basic types of radiation:

Sound waves are an exmple of a mechanical vibration. The energy is transmitted through a material medium by pressure variations. This type of radiation is presented in Concept Module 11-0, "Vibrations and Waves" and will not be discussed further here.

Light is an example of electromagnetic radiation, in which energy is transnitted by variations in electric and magnetic fields. Electromagnetic radiation requires no material medium and will travel through a vacuum.

Alpha and beta particles are examples of particle radiation, in which a particle having mass transmits energy in the form of the kinetic energy of its mass.

This module begins with a discussion of simple experimental methods for the creation of radiation. Then the family of EM radiations is examined; this family is neatly arranged according to frequency (or wavelength) in the so-called "electromagnetic spectrum." A study is made of the fundamental similarity of all EM radiation, as well as of the fundamental difference between the individual parts.

Next, a simple picture is presented of just what makes up an electromagnetic wave and how much radiation is propagated in empty space. Following this is (1) a closer look at the origin of visible, infrared, and microwave radiation in the structure of atoms and molecules; and (2) an examination of a few characteristics of radiation — the inverse-square radiation law, polarization reflection, and radiation. Quite apart from radiant energy, particle radiations, such as alpha and beta rays, are presented. Several laboratory experiments that verify some of the characteristics are included.

RADIANT ENERGY (EM RADIATION) - BASICS

The creation and observation of electromagnetic (EM) radiation is not difficult when a simple incandescent light bulb is turned on in a dark room; visible EM radiation (light) immediately floods the room. Electrical energy pulsing through tungsten filaments in the bulb is converted into visible radiation. Invisible thermal radiation (heat) also is produced, since the glass envelope becomes hot. Thus, both light and thermal radiation are created.

Consider another common example. In the process of jumping cables from the terminals of one car battery to another, a large

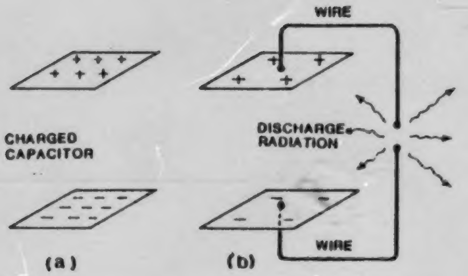


FIG. 1

spark is drawn, especially if the hot wire touches the ground wire. Spark, or discharge flash, is a pulse of radiation energy, partly in the visible and partly in the invisible. Charged capacitors (Figure 1) also produce a spark, or discharge flash, when shorted out, sending a pulse of radiation energy out into the surrounding space. The charged isolated capacitor is shown in (a); the partially discharged capacitor and the EM radiation produced is shown in (b).

Still another common example of EM radiation involves the kitchen toaster. When the toaster is plugged in, the resistive coils increase in temperature. The toaster coils first are observed to be a dull red, then a cherry red, and finally a pinkish-white color. At the beginning of the heating process, the coils radiate primarily thermal energy. The warmth of the wires can be felt, although no color change is observed. Shortly, however, the wires become hotter, change color as described, and then clearly radiate both thermal and light energy.

Since total energy is to be conserved in any system, such as in those described, radiation energy, an integral part, must be conserved. Total work done in a system can be described as follows:

Work done on system = change in kinetic energy + change in potential energy + frictional losses + EM radiation

In mechanical energy systems, no EM radiation is produced. But in electrical energy systems (which involve the movement of electrical charge), EM radiation almost always is produced. For example, immerse a light bulb in a calorimeter and turn the light bulb on for a given period of time T. Carefully measure the temperature of the calorimeter before the light bulb is turned on and again a time T later. The electrical energy supplied to the bulb is given by IVT, where I is the current in amperes, V the voltage in volts, and T the time in seconds. Measurement of the heat energy absorbed by the calorimeter in the same time T, shows that the electrical energy absorbed by the bulb (IVT) does not quite equal the heat energy absorbed by the calorimeter. The input energy is higher! The difference, of course, is equal to the visible, or light, energy which radiated outwards continually while the bulb was on, but was not used in heating the calorimeter. Thus, if energy is to be conserved, as it always must be, all EM radiation must be limited where possible.

THE ELECTROMAGNETIC SPECTRUM

Electromagnetic radiation is a form of energy stored in time-changing electric and magnetic fields. The time-changing electric and magnetic fields always are set into motion by the acceleration of electric charge, whether in a radar or FM transmitting antenna, in a discharging capacitor, or in an a.c. current in a simple light bulb or toaster. Invariably, the exact manner in which the electric charge acceleration occurs always is related to the particular type of electromagnetic radiation that develops. Charge accelerations can be produced in many ways: by varying the motion of charges on an electric conductor (such as on an antenna); by heating a material to increase vibrational energy of charged particles (such as in a tungsten filament); or by causing a charged particle to change its direction (such as in a.c. current).

The different types of EM radiation produced have been identified and organized in accordance with their frequency, or wavelength, range in the so-called ME spectrum. (See Figure 2.) The top scale in Figure 2 identifies frequency from 10 hertz to 10^{22} hertz. The bottom scale identifies the corresponding wavelength from about 10^7 meters down to 10^{-13} meters. Thus, at the left end of the EM spectrum is found the very low-frequency, very long-wavelength radiation, such as a.c. power and radio waves. At the other end is found the very high-frequency, very short-wavelength radiation, which includes the very penetrating x-rays and gamma rays.

The wavelength λ and frequency f for any part of the EM spectrum are related by Equation 1 (the fundamental equation).

$$c = \lambda f \qquad (1)$$

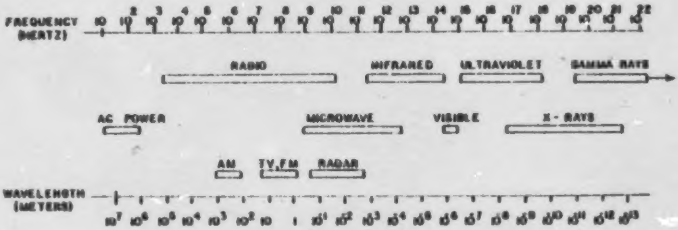

FREQUENCY (HERTZ)
10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21 10^22
RADIO
INFRARED
ULTRAVIOLET
GAMMA RAYS
AC POWER
MICROWAVE
VISIBLE
X - RAYS
AM
TV,FM
RADAR
WAVELENGTH (METERS)
10^7 10^6 10^5 10^4 10^3 10^2 10 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12 10^-13

FIG. 2

where

c = wave speed in meters per second.
λ = wavelength in meters.
f = frequency in hertz (cycles per second).

In free space or vacuum, the speed of EM radiation is a constant equal to 299,792,500 meters per second. (For calculations this number usually is rounded off to 3.0×10^8 m/s.)

The energy associated with electromagnetic radiation is given by Equation 2.

$$E = hf \qquad (3)$$

where

E = energy in joules.
h = famous constant known as Planck's constant and equal to 6.6×10^{-34} J·s.
f = radiation frequency in hertz.

If Equation 1 is used to replace f in Equation 2 by $f = c/\lambda$, then an equivalent form for Equation 2 is shown in Equation 3.

$$E = \frac{hc}{\lambda} \tag{3}$$

Equations 1 and 2 are used to solve problems in Examples A and B, which show that the higher the frequency (or the lower the wavelength), the higher the energy of the EM radiation. This relationship should be clear from the forms of Equations 2 and 3.

Before leaving the discussion on the EM spectrum, examine Figure 1; and briefly describe some of the more important types of EM radiations.

EXAMPLE A: FREQUENCY AND ENERGY OF VISIBLE RADIATION (LIGHT)

Given: A light has a wavelength of between 400 nanometers (blue) and 700 nanometers (red).

Find: The corresponding frequency and energy of the blue and red light.

Solution: Blue light: (λ = 400 nanometers = 4×10^{-7} m)

From Equation 1: $f_B = \frac{c}{\lambda_B} = \frac{3 \times 10^{8}}{4 \times 10^{-7}} = 7.5 \times 10^{14}$ hertz

From Equation 2: $E_B = hf_B = (6.6 \times 10^{-34})(7.5 \times 10^{14})$

$E_B = 50 \times 10^{-20}$ joules

Red light: (λ = 700 nanometers = 7×10^{-7} m)

Similarly, $f_R = \frac{c}{\lambda_R} = \frac{3 \times 10^{8}}{7 \times 10^{-7}} = 4.3 \times 10^{14}$ hertz

$E_R = hf_R = (6.6 \times 10^{-34})(4.3 \times 10^{14})$

$E_R = 28 \times 10^{-20}$ joules

EXAMPLE 8: ENERGY COMPARISON

Given: A radio wave has a frequency of 800 kilocycles and a gamma ray of wavelength 10^{-13} meters.

Find: The ratio of their energies.

Solution: Energy of radio wave: use Equation 2, $E = hr$.

$$E_{RW} = 6.6 \times 10^{-34} \times 8 \times 10^{5} = 53 \times 10^{-29} \text{ joules}$$

Energy of gamma ray: use Equation 3, $E = hc/\lambda$.

$$E_G = \frac{(6.6 \times 10^{-34})(3 \times 10^{8})}{10^{-13}} = 20 \times 10^{-13} \text{ joules}$$

Thus,

$$\frac{E_G}{E_{RW}} = \frac{20 \times 10^{-13}}{53 \times 10^{-29}} = 3.8 \times 10^{15}!$$

So the energy of the gamma radiation is about one thousand million million times more energetic than a 800 kilohertz radio wave!

RADIO WAVES

EM radiation with frequencies between 10^4 and 10^7 hertz and wavelengths from tens to thousands of meters are identified as radio waves. They are reflected effectively by charged layers in the upper atmosphere and, therefore, can propagate over long distances from the radio station. The AM frequency band on most table radios varies from 530 kilohertz to 1600 kilohertz.

TELEVISION AND RADAR

Television and FM broadcasting stations make use of EM radiation with frequencies of about 10^8 hertz and wavelengths of about one meter. Most FM dials are calibrated between 85 and 110 megahertz. If the radiated signal is in the form of pulses, the time from emission of the pulse to the reception of its reflected signal (the echo) can be used to determine the distance from source to reflecting object. This is the principle of radar (Radio Detection And Ranging). As Figure 2 indicates, radar is pulsed EM radiation of frequency between 10^9 and 10^{11} hertz and wavelength ranging from a centimeter up to a meter. By means of radar, both the direction and distance of an object can be measured.

INFRARED RADIATION

Radiation with wavelength between 10^{-4} and 10^{-6} meters generally is classified as infrared radiation. It is called "infrared" because most of the radiation is in a region of the spectrum at which the wavelengths are slightly longer than the red end of the visible spectrum. Infrared radiation is emitted by all hot bodies, such as the sun, toasters, room radiators, and soldering irons.

VISIBLE LIGHT

The human eye is sensitive to electromagnetic radiation between 400 and 700 nanometers, and this EM radiation is detected directly with the eye. It has come to be known as "light." The eye reacts most sensitively to the green and yellow colors near 555 nanometers and least sensitively to the far red (where the invisible infrared begins) and to the far blue (where the invisible ultraviolet light begins).

ULTRAVIOLET LIGHT

EM waves shorter than 400 nanometers and longer than ten nanometers (between 10^{15} and 10^{18} hertz) are classified as "ultraviolet" light. Ultraviolet (uv) light, or "black light," as it sometimes is called, is invisible. It is more energetic than either infrared or visible light and causes summer suntans by producing a dark skin pigment known as "melanin." Many atoms emit characteristic uv light during processes of de-excitation. As a result, spectroscopists use the uv "fingerprints" to identify atoms from their characteristic emissions.

X-RAYS

The region of the EM spectrum with radiation of wavelgnths between 10^{-8} and 10^{-17} meters frequently is referred to as "x-radiation" or, more simply, as "x-rays." This radiation is so energetic that it can penetrate tissue and flesh, but not bone, therefore making possible x-ray photographs of the human skeletal frame. X-rays are produced by the sudden deceleration or stopping of electron beams as they strike a metal target. X-rays, with wavelengths roughly comparable to the distance between planes of atoms in crystallographic substances, have been diffracted readily. Such diffraction of x-rays has led crystallographers to important information concerning the structure of crystals and of complex molecules.

GAMMA RAYS

Gamma radiation, very penetrating and very energetic, extends beyond the x-ray region, although some overlapping does exist. Since an x-ray and gamma ray can exist with the same wavelength, frequency, and energy, and are identical, therefore, as EM radiations, how are they distinguished? The answer lies in how they are produced. If the production of EM radiation of wavelength 10^{-17} meters occurs by electron rearrangement in the region of the atom outside the nucleus, the radiation is referred to as x-rays. If the same wavelength radiation is produced by a rearrangement of neutrons and protons in the nucleus, it is referred to as a gamma ray. If EM radiation of 10^{-17} meters is encountered in the laboratory without knowing its origin, it is not known whether it is an x-ray or a gamma ray.

This overlapping of EM radiations (Figure 2) occurs not only for x-radiation and gamma radiation, but also for radio, microwave, and radar. In the overlap region, a decision is required to determine whether it is a radio wave, a microwave, or a radar wave, depending upon how it is produced.

Gamma rays often are discussed in conjunction with alpha and beta rays, which is quite natural, since all three generally are created in nuclear transformations. In fact, the creation of alpha and beta rays in nuclear decay processes almost always is accompanied by the creation of gamma rays. But gamma rays are electromagnetic in character, while alpha and beta rays are particulate in nature. Thus, they fundamentally are different. Particle radiation will be discussed in more depth later in this module.

THE NATURE OF ELECTROMAGNETIC WAVES

Electromagnetic radiation is an electromagnetic wave of specific frequency, moving through space with a speed $c = \lambda f$. The electromagnetic wave itself (Figure 3) consists of propagating electric and magnetic fields E and H, which vary with time as they move along the direction of propagation. The electric field E is shown oscillating in the y-direction and always in the xy plane. The magnetic field H is shown oscillating in the z direction and always in the xz plane, perpendicular to the electric field E. The radiation energy contained in the wave is shown propagating along the positive x-axis. The maximum value that the electric field E attains while oscillating is labeled E_m; that for the magnetic field H is labeled H_m.

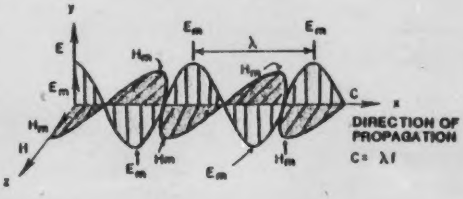


FIG. 3

As explained earlier in Application Module IE4, an electric field exists at a point in space if a force of electrical origin is exerted on a charged body placed at that point. A force of electrical origin always is produced by the presence of other charged bodies, either positive or negative, and by a magnetic field changing with time. In order to help visualize the electric field around different electric charge configurations or in the vicinity of time-changing

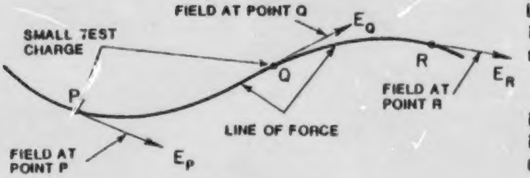
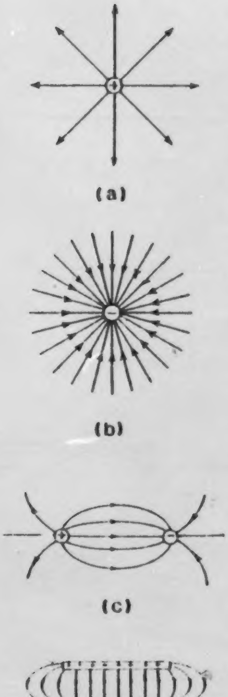


FIG. 4



(a)

(b)

(c)

(d)

FIG. 6

magnetic fields, the idea of lines of force was introduced in the early 1800s by Michael Faraday, a pioneer in unraveling the mystery of electromagnetic radiation.

An electric line of force is an imaginary line drawn in such a way that its direction at any point — that is, the direction of its tangent — is the same as the direction of the electric force on a very small, positive "test" charge placed at that point. (See Figure 4.) If the number of field lines which are drawn to represent the electric field in a given region are suitably limited, they can be used to indicate visually the magnitude of the field, as well as its direction. Figure 5 shows electric lines of force that surround different configurations of electric charge. The density of lines indicate the relative strength of the electric field. The arrows indicate the direction of the field. Notice that force lines always point in the direction of the net electric force on a small positive "test" charge placed at that point. The "test" charge samples the existing electric field without disturbing or changing it. Figure 5a shows the field surrounding a weak positive charge; the direction of the field is away from the positive charge. Figure 5b shows a stronger negative charge and the electric field it produces. In this case, direction of the field is toward the negative charge. Figures 5c and 5d show the electric field produced by a pair of point charges and the field between two charged parallel plates.

Similarly, as presented in Application Module IE4, a magnetic field exists in regions surrounding ordinary bar magnets, and moves electrical charge as in current-carrying conductors and in the region where an electric field is changing with time. A magnetic field is evidence of a magnetic force, different from the electric force described above. A magnetic force is sensed by a moving charge, in addition to an electric force sensed by the same moving charge.

Magnetic lines of force, like electric lines of force, are used to help visualize a magnetic field. Like the lines of electric force, they are imaginary. The magnetic lines of force at a given position in space always point in the direction of the net magnetic force on a small, imaginary, "free" north pole placed at that point. (Of course, "free," or isolated, north poles do not exist, as do small positive "test" charges. The existence of a north pole always implies a south pole nearby. But these facts do not prevent the direction of force on such a "free north pole" from being deducted if there is one; definitions for the direction of magnetic lines of force remains valid and useful.)

Magnetic lines of force around bar magnets and certain configurations of moving charge are illustrated in Figure 6. The magnetic field surrounding a simple bar magnet is shown in 6a, and Figure 6b illustrates the field produced when the south pole of one magnet is placed near the north pole of another. Figure 6c displays the field of a solenoid with a current flowing in the direction indicated. The right end of the solenoid is a south pole, and the left end is a north pole. The magnetic lines of force in a plane perpendicular to a wire carrying a d.c. current are shown in 6d.

The representation of electric and magnetic fields as lines of force may be used to illustrate the important principle mentioned earlier; that is, that a time-changing electric field in space produces a magnetic field nearby, and a time-changing magnetic field in space produces an electric field nearby.

Figure 7 illustrates how a changing electric field E developed between two conducting plates produces a magnetic field. In 7a, a static electric field exists in the region between the plates (vertical arrows from bottom plate to top plate). In 7b, the electric field E begins to increase, thereby creating a magnetic field H (concentric circles about axis of plates). In 7c, the electric field continues to grow rapidly, creating an even more intense H field. In 7d, the electric field is still increasing, but more slowly; the H field begins to decrease. In 7e, the electric field has reached its maximum value and is no longer changing; the H field has vanished. In 7f, the electric field begins to decrease; again a magnetic field is produced but now in the opposite direction. In 7g, the electric field is decreasing rapidly, thereby producing a strong H field. In 7h, the electric field decreases more slowly so the magnetic field H begins to weaken. In 7i (same as 7a), the electric field has decreased to its original static value, and the H field has vanished.

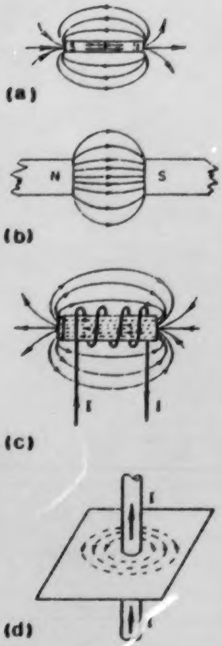


FIG. 6

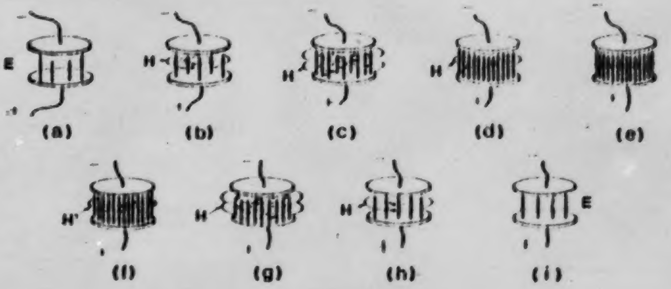


FIG. 7

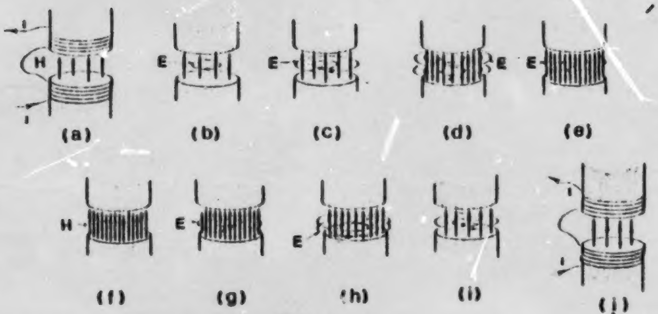


FIG. 8

In Figure 8a, the changing magnetic field H developed between the two poles of the electromagnet in 8a, produces a magnetic field. As the current I through the coils increases, the magnetic field increases in strength (8b, 8c, 8d, and 8e); and an electric field is produced (concentric circles around axis of electromagnet). The strength of the E field is greatest at the instant the magnetic field is increasing the fastest (8d). When the magnetic field has reached its maximum value (8f), the electric field is zero, since the H-field is not changing. Then, as the magnetic field begins decreasing (8g, 8h, 8i) because of a decreasing current in the coils, the electric field again builds to a maximum (8h) and eventually disappears (8j) when the magnetic field returns to its original static value (8a).

The conclusion drawn from Figures 7 and 8 is very important. It provides an explanation of how EM radiation is able to propagate through empty space, quite unlike sound, for example, which requires a medium, or substance, for its transmission. Begin only with a source such as an antenna, where electric charge is accelerated. The physical process of accelerating charge creates a time-changing electric field and magnetic field near the source. Each time-changing field, in turn, creates the other, as shown in Figures 7 and 8, thereby sustaining the progagating electric and magnetic fields (electromagnetic waves or electromagnetic radiation) throughout space. Figure 9 consists of a drawing (similar to Figure 3, except in two dimensions) of a plane EM wave propagating away from a "horn." Internally, electric oscillations in an electronic circuit are led onto an antenna-like

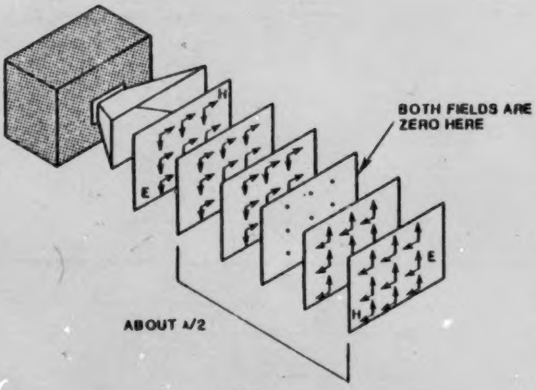


FIG. 9

rod in the conducting horn. There, electric and magnetic fields are generated and radiate out into space, as shown. The H field vibrates from left-to-right, and the E field vibrates up and down. Notice the plane at which both fields go to zero. Notice, also, that when E reverses — goes from "pointing-down" to "pointing-up" — H also reverses, switching from right to left. (Can you justify the note on the drawing about λ/2?)

EM RADIATION - WAVES OR PHOTONS

Inevitably, while learning about electromagnetic energy, one hears EM radiation or energy referred to sometimes as a "wave" and sometimes as a "photon." The idea of waves is very familiar. Therefore, use is made of the concept of waves in describing EM radiation thus far. A photon — similar to a localized EM wave, truncated at both ends (Figure 10) — is not so familiar. Yet the concept of a photon, which is more like the concept of a particle than of a wave, is necessary for one to comprehend EM radiation. EM radiation sometimes is best described as a wave (radar, for example) and at other times best described as a photon (gamma rays, for example).

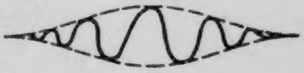


FIG. 10

Light often is referred as a wave phenomena and thought of as matter being made up of particles. Waves are described in terms of amplitude, wavelength, frequency, and energy. Particles, on the other hand, are described in terms of size, mass, momentum, and energy. Visible light waves and radio waves do not exhibit particle properties readily, and particles large enough to be seen with the eye (dust particles, B-B's, baseballs) do not resemble waves. The particle properties of radar and radio-frequency photons are not apparent, because they are of such low energy that only large numbers of them (not single ones) can be detected. When detected in large numbers, radar and radio-frequency photons with comparatively long wavelengths behave exactly like waves. However, the shorter-wavelength, more energetic EM radiations, like energetic and gamma rays, are detectable as "single particles." They do, for example, exhibit true particle properties and are best treated as photons. Not only are waves often described best in terms of particle properties (photons), but very small particles (atoms, electrons, protons) sometimes are described best as waves. These descriptions, by the way, are what quantum mechanics is all about.

The dual nature of EM radiation becomes apparent in the x-ray region, since x-ray photons exhibit both wave and particle properties. Gamma rays, with wavelengths much shorter than x-rays, exhibit primarily particle properties and are treated primarily as photons. In general, EM radiation is treated as a wave when it is of long wavelength (low energy) and when the propagation, reflection, refraction, interference, or diffraction of EM energy is under investigation. EM radiation is treated as a particle (photon) when it is of short wavelength (high energy) and when its interaction with matter (absorption, scattering, transmission) is under investigation.

Before leaving this fascinating topic of waves and photons, a few words about the origin of EM radiation in the visible, infrared, and microwave regions of the EM spectrum are desirable. Most of the visible light seen comes from changes in configurations of electrons within the atom. Thus, when an atom absorbs energy in some form, its electrons pick up this energy and are repositioned further away from the nucleus. When the "excited" atom releases the absorbed energy and, in the process, the electrons are returned to their original configuration, the released energy comes off as short bursts of EM radiation — photons. The frequency of this emitted EM radiation — when it lies between 4.3×10^{14} hertz (red light) and 7.5×10^{14} hertz (blue light) — constitutes the visible part of the spectrum.

In addition to the energy stored in various configurations within the atom and later emitted as light energy, energy also is stored in the vibrational and rotational modes of several atoms locked together in the form of molecules. If the stored molecular energy is of vibrational form (two atoms vibrating back and forth as in the CO molecule) and then released, the EM radiation given off is primarily infrared radiation. Thus, heat energy, which is EM radiation in the infrared region, has its origin in the excess vibrational energy stored in molecules. If the molecular energy is stored as rotational energy (for example, a diatomic molecule rotating around its center of mass like a rigid bar bell) and then released, the EM radiation is given off primarily as microwave radiation.

When studying the processes involved in the emission and absorption of visible, ultraviolet, infrared, or microwave radiation, the concept of short bursts of energy (photons), rather than of long unending wave trains, best describes what is taking place. Thus, the phenomena of absorption and emission of EM radiation are described and most easily understood in terms of wave packets or photons of EM energy.

SOME CHARACTERISTICS OF EM RADIATION

Since EM radiation is fundamentally an electromagnetic wave, it exhibits all the behaviors expected of waves propagating through space and passing through and around objects. Thus, EM radiation is expected to be reflected and refracted; to diminish in strength, or attenuate, as it spreads out from a source; to be polarized in some instances; to show interference when it overlaps itself; and to be diffracted when it passes through small portholes or around small objects. Here "small" refers to a dimension of the order of the wavelength of the EM radiation in question. Clearly, "small" refers to two entirely different dimensions with reference to radio waves and x-rays.

REFLECTION

The law of reflection of EM waves is illustrated in Figure 11. The ray shown in Figure 11 can be thought of as the x-axis (or direction of propagation) of the E and H fields shown in Figure 3. Notice that in Figure 11, the incident ray, reflected ray, and normal all lie in the same plane and define the plane of incidence. Angle A, the angle of incidence, is equal to angle B, the angle of reflection. The law of reflection of EM waves is given by Equation 4.

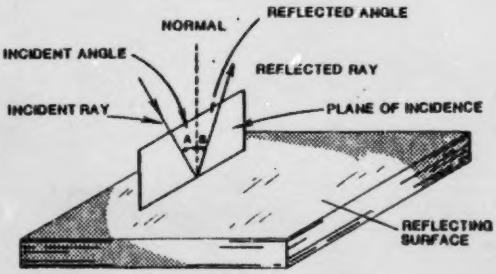

NORMAL
REFLECTED ANGLE
INCIDENT ANGLE
REFLECTED RAY
INCIDENT RAY
PLANE OF INCIDENCE
A
B
REFLECTING SURFACE

FIG. 11

$$\angle A = \angle B \qquad (4)$$

where
$\angle A$ = angle reflection.
$\angle B$ = angle of incidence.

REFRACTION

The law of refraction of EM radiation is given by Equation 5 and illustrated in Figure 12. Again,

$$n_a \sin A = n_c \sin C \qquad (5)$$

where
n_a = index of refraction of incident ray.
n_c = index of refraction of ray in material.

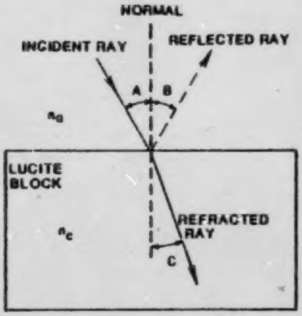

NORMAL
INCIDENT RAY
REFLECTED RAY
A
B
n_a
LUCITE BLOCK
n_c
REFRACTED RAY
C

FIG. 12

Use is made of rays that indicate the direction along which the EM radiation propagates. The index of refraction n is a constant characteristic of the material and is merely the ratio of the speed of light c in a vacuum to the speed of light v in that material. For air, the index of refraction n is nearly 1.00. For lucite and most glasses, it is around 1.50.

POLARIZATION

An examination of Figures 3 and 9 presented earlier discloses two facts. First, the vibration of the electric (E) and magnetic (H) fields always is perpendicular to the direction of progagation of the EM wave. This has come to be recognized as the transverse nature of EM radiation. Second, in Figure 3 the E-vibration always is in the y-direction, and the H-vibration is always in the z-direction. Such a restriction of vibration of E or H along a single direction is called "polarization." Thus, the electric field is said to be polarized along the y-direction, and the magnetic field to be along the z-direction. The direction of propagation is along the x-direction. Similarly, in Figure 9 the EM radiation is polarized linearly; the H-field is polarized left-to-right; and the E-field is polarized up and down.

INVERSE-SQUARE LAW

If a person stands some distance from a 100-watt lamp bulb (far enough away that the distance from the bulb is large compared to the size of the bulb), the bulb can be observed and treated as if it were a "point" source of EM radiation. The power radiated by the bulb decreases as the square of the distance between the receiver and the bulb. Thus, if the power per unit area is measured to be P_o when 10 feet away, the power per unit area will be $P_o/4$ when 20 feet away and $P_o/9$ when 30 feet away, and so on. This rapid decrease in power with doubled and tripled separations is known as the inverse-square law and is given in simple form by Equation 6:

$$P = \frac{P_o}{d^2} \qquad (6)$$

where

P = power per unit area falling normally on a collecting surface a distance d from the light source.
P_o = power per unit area falling normally on a collecting surface a distance d of unit length from the light source.

PARTICLE RADIATION

As previously stated in this module, "particle radiation" is very different from "electromagnetic radiation," although both use the genertic term "radiation." Gamma rays (an electromagnetic radiation) differ significantly from alpha and beta rays (particle radiation), although all are created during nuclear transformations and, therefore, usually discussed together. In order that the difference between electromagnetic radiation and particle radiation can be clarified, the origin and characteristics of alpha and beta radiation must be examined.

Recall that atoms are composed of a positive nucleus surrounded by negative electrons. The nucleus contains both protons and neutrons. Protons have a mass equal to that of 1836 electrons and have an electronic charge of +1. (Electrons have a charge of -1.) Neutrons have a slightly greater mass than protons and have a charge of zero. Under certain conditions, a neutron in an atomic nucleus may divide into a proton (+1) and an electron (-1).

Beta radiation, or beta rays, is a stream of very energetic electrons emitted from the nucleus during the instant at which neutrons are converted to protons within the nucleus, therefore, beta rays really are electrons born in the nucleus! Alpha rays are also particles — the nuclei of helium atoms, in fact, and about 7500 times heavier than the electrons in beta rays. The alpha particles, like beta particles, also are created in the nucleus and emitted during a nuclear transformation. Often, alpha, beta and gamma radiation are referred to as a group; however, alpha and beta rays refer to streams of energetic particles, and gamma rays, like x-rays, refer to energetic electromagnetic radiation. Both x-rays and gamma rays have particle-like properties and often are treated as photons rather than as waves, but they remain fundamentally electromagentic waves and not particles.

ALPHA RAYS

As mentioned above, the alpha particle is the nucleus of a helium atom expelled from a heavy element during the nuclear transformation from one element to another. Thus, for example, when uranium-238, which has 92 protons and 146 neutrons clustered together in its nucleus, changes, or "decays," to thorium-234 (90 protons and 144 neutrons), an alpha particle is emitted from the nucleus. This alpha particle (uranium-238) has two protons and two neutrons, just as does the fully-ionized helium atom. In terms of common nuclear symbols, the nuclear reaction discussed here is given as follows:

$${}_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}He^{4}$$

Notice that superscripts (mass numbers) and subscripts (atomic numbers) obey a conservation law; thus, $238 = 234 + 4$, and $92 = 90 + 2$. The element uranium-238 is written as ${}_{92}U^{238}$, where the subscript 92 refers to the number of protons in the nucleus (atomic number), and the superscript 238 refers to the sum of protons (92) and neutrons (146) in the nucleus (atomic mass numbers). The reaction equation shows that an alpha particle ${}_{2}He^{4}$ is created when uranium-238 decays to thorium-234.

Alpha particles usually are very energetic, but are able to travel only short distances in matter because of their excessive mass. (As mentioned above, the alpha particle is about 7500 times as massive as the electron.) Although most alpha particles are created with energies from 4 million electron volts to 9 million electron volts (with corresponding velocities around 1.4×10^7 m/s to 2.1×10^7 m/s), almost all alpha particles can be stopped by a single sheet of paper. (Note: one electron volt is the energy acquired by an electron accelerated through a potential difference of one volt.) The range of alpha rays in air can be remembered by use of a general rule of thumb — about 1 cm of air for each 2 million electron volts of energy. Even in air, therefore, the most energetic alpha particles will not travel more than about three or four inches.

BETA RAYS

Electrons emitted by radioactive nuclei are called "beta particles" (or beta rays) — a name given to them before they were identified as electrons. So beta rays, as mentioned above, are nothing more than high-energy electrons created in the nucleus. Since, so far as known, there are no electrons as such in the nucleus, they must be created during the nuclear transformation itself. This process is explained in the following manner: a neutron (which does exist in the nucleus) is converted to a proton (which also can exist in the nucleus) by creating an electron. In terms of a nuclear reaction equation, this relationship is written —

$${}_0n^1 \rightarrow {}_1p^1 + {}_{-1}e^0.$$

In essence, the equation states that a neutron with charge zero and mass number one (written ${}_0n^1$) is converted to a proton of charge one and mass number one (written ${}_1p^1$) and an electron of charge minus one and mass number zero (written ${}_{-1}e^0$).

The process described above occurs in many nuclear transformations, thereby giving rise to beta rays. An example of such a transformation is —

$${}_{82}Pb^{214} \rightarrow {}_{83}Bi^{214} + {}_{-1}e^0.$$

Radioactive lead 214 decays to the isotope bismuth-214, and in the process emits a beta particle (a high-speed electron). Since a neutron was converted into a proton within the nucleus, the mass number 214 (sum of protons and neutrons) remains the same before and after the transformation. But the atomic numbers (number of protons) increases by one, going from 82 to 83, because a neutron in the nucleus was changed to a proton.

The penetration of matter by the beta particles generally is much higher than that by alpha particles. A single sheet of paper stops most alpha particles; a ream of paper (or several centimeters of aluminum) is required to stop beta particles. The range of energy values for beta particles is not defined as clearly as for alpha particles. In fact, beta rays have a continuous energy distribution, with the energy of a typical beta particle lying around a few hundred thousand electron volts. However, the velocity of the beta particles is about 2.7×10^8 m/s (nine-tenths the speed of light), considerably higher than that of the alpha particle.

The beta particle must move with a much higher speed than an alpha particle of the same energy, since the beta particle is so much lighter in mass. Beta particles move deeper into matter than alpha particles, because of their higher speeds and lesser net charge.

Table 1 summarizes the important characteristics of alpha and beta particles.

TABLE 1: CHARACTERISTICS OF α AND β PARTICLES

	Symbol	Mass	Charge	Approximate Energy	Range
Alpha Particle	α, ${}_{2}He^{4}$	6.69×10^{-27} kg	3.2×10^{-19} C	4-9 MeV	Stopped by one sheet of paper
Beta Particle	β, ${}_{-1}e^{0}$	9.1×10^{-31} kg	1.6×10^{-19} C	~ 1 MeV	Stopped by one ream of paper

REFLECTION AND REFRACTION OF EM RADIATION

MATERIALS

Low-power He-Ne laser (1-3 milliwatts).
Optical material with plane parallel surfaces and an index of refraction of about 1.5 (a large block of lucite or acrylic plastic works well).
Front-surface plane mirror.
Drafting paper, protractor, and sharp pencils.

PROCEDURE

In this experiment, the laws of reflection and refraction with EM radiation (laser light at 6328 Å in the visible region of the EM spectrum) will be verified. Observe safety precautions when using laser light! Never look into the direct beam or permit the reflected beam to enter the eyes!!

REFLECTION

1. Set up experimental apparatus as shown in Figure 13.

2. Place center of front-surface plane mirror flush with base of protractor at center of rotating mount.

3. Raise or lower rotating mount so that laser beam just grazes protractor surface and strikes mirror at the center of mount. Light is then reflected straight back towards the laser. Rotate mount to five different settings (10°, 20°, 30°, 40°, 50°) and record angle of incidence and angle of reflection in Data Table. (If laser beam grazes top surface of the protractor properly, both angle of incidence and angle of reflection can be read directly off the protractor.) Verify law of reflection.

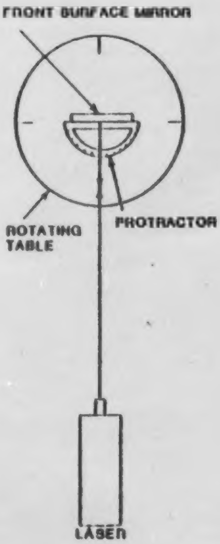


FIG. 13

REFRACTION

1. Draw a straight line NN on a large piece of drafting paper, as shown in Figure 14.

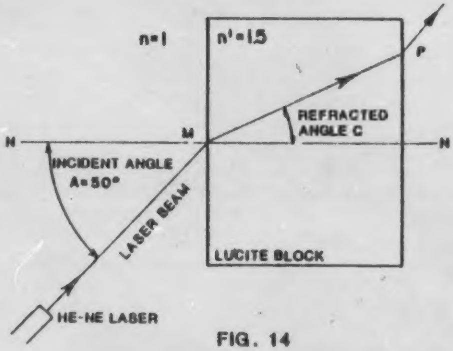


FIG. 14

2. Align lucite block in such a manner that one of its parallel surfaces is perpendicular to line NN at M.

3. Orient low-power He-Ne laser in such a manner that laser beam is incident on lucite block at point M and makes an angle of 50° with line NM. Clearly mark point M.

4. Locate and mark P where laser beam emerges from lucite block on opposite side. Now remove block and draw line MP.

5. Measure refracted angle C with protractor.

6. Now calculate angle C from law of refraction ($n_a \sin A = n_c \sin C$). Remember that $n_a = 1$, $n_c = 1.5$ and angle A = 50°.

7. Compare calculated value of C in step 6 with measured value in step 5. Account for any difference.

8. The laser beam leaving the lucite block at point P should be parallel to the incident laser beam (50°) at M: Draw the exiting ray, and repeat steps 5, 6, and 7 for point P, taking care to redefine the angles of incidence and refraction properly for point P.

POLARIZATION OF EM RADIATION

MATERIALS

Laboratory microwave transmitter (wavelength around 3 cm).
Laboratory microwave receiver or detector.
Microwave grid analyzer (a series of parallel wires with spaces of about 1/10 wavelength).

(Note: The entire microwave demonstration kit is available from CENCO or WELCH laboratory apparatus companies.)

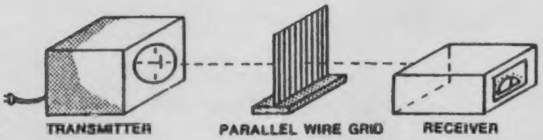


FIG. 15

PROCEDURE

EM radiation emitted by the mircrowave transmitter is polarized. Arrange transmitter, grid, and receiver as shown in Figure 15.

1. Remove grid, turn on transmitter, and move receiver (also adjust sensitivity) to record direct beam at near full scale.

2. Replace grid, and slowly rotate it from an orientation with wires vertical, as shown in Figure 15, to an orientation with wires horizontal. Observe receiver reading carefully as grid is rotated.

3. At what angle of rotation of grid (orientation of wires measured from vertical) did receiver read its minimum value? (Repeat step 2 until same reading can be reproduced several times without trouble.)

4. From observation in step 3, determine direction of polarization of the E and H field in microwave radiation. (Consult instructor if necessary.) Once certain of answer, draw a representation of EM field similar to that shown in Figure 9, with correct E and H polarizations. Draw sufficient planes to cover one wavelength of variation in E and H.

INVERSE-SQUARE LAW

MATERIALS

Photographic light meter.

PROCEDURE

In a room in which all light can be extinguished, arrange a test lamp and photographic light meter on a long table, as shown in Figure 16.

1. Locate photographic light meter at a distance $d = D_1$ from a frosted incandescent lamp (choose the 100-watt bulb initially) in such a manner that light meter registers nearly full scale when lamp is on and all other room lights are turned off. Ensure that front surface of the light meter is perpendicular to line joining center of lamp and center of light meter (line AB in Figure 14). Record initial reading P_1.

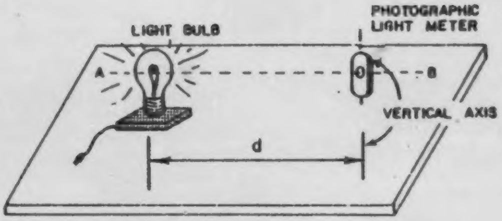


FIG. 16

2. Carefully move light meter away from lamp along line AB; and take successive light-meter readings at 1.5 D_1, 2 D_1 and 3 D_1. Ensure that face of light meter is normal to line AB when taking each reading. (Rotate light meter back and forth about its vertical axis, as shown in Figure 15, until highest reading is recorded. Face of light meter then should be normal to the line AB.)

3. Using Equation 6 ($P = P_O/d^2$), verify the inverse-square law by showing that P_2 (at $d = 1.5\ D_1$) is equal to (1/2.25) P_1; that P_3 (at $d = 2\ D_1$) is equal to (1/4) P_1; and that P_4 (at $d = 3\ D_1$) is equal to (1/9) P_1.

4. Repeat the entire procedure for 40-watt bulb. How well did the results verify the inverse-square law dependence of power per unit area on distance?

Note: Possible errors include the following:

1. Light meter too close to lamp. Recall that the law is valid only for point sources and that the bulb is not a point source. The distance D_1 should be at least ten times the diameter of the bulb. Results for the 100-watt lamp should be more valid than for the 40-watt lamp, since the light meter for the 100-watt lamp will be further away for the initial full-scale reading.

2. Room light, other than from bulb striking the light meter.

3. Surface of light meter not perpendicular to line AB at time of readings.

4. Illuminance scale on light meter too difficult to read accurately.

SELF CHECK

1. Discuss the basic properties of these types of radiation:

   Sound.
   Light.
   Alpha and beta particles.

2. What is electromagnetic radiation (radiant energy)? Describe a simple experiment that demonstrates how electromagnetic radiation can be created.

3. The microwave demonstration transmitter sold by the Welch

Scientific Company emits microwaves of 3 cm wavelength. Determine the frequency (hertz) and energy (joules) of the microwaves.

4. The eye is most sensitive to visible light at 555 nanometers. What is the frequency of this light? What is its color? What is its energy?

5. A 150-watt incandescent lamp hangs 8 feet above the surface of a study desk. How close to the desk must it be moved to increase the power per unit area falling on the surface by a factor of six?

6. From Figure 2, the EM spectrum, determine the midpoint frequency for each EM radiation shown (from a.c. power to gamma rays), and calculate the corresponding wavelength and EM wave energy. Present results in the Data Table.

7. What is the difference between a low energy gamma ray of frequency 10^{20} hertz and a high-energy x-ray of the same frequency? Explain.

8. A gamma ray photon has an energy of 3 million electron volts. (One electron-volt of energy is equal to 1.6×10^{-19} joules.) What is the frequency and wavelength of this photon? What is its speed in glass ($n_{glass} = 1.5$)?

DATA TABLE

EM Radiation	Mid-Frequency (From Figure 2)	Wavelength (Calculated)	Energy (Joules) Calculated
a.c. power			
Radio			
AM			
TV, FM			
Radar			
Microwave			
Infrared			
Visible			
Ultraviolet			
X-rays			
Gamma rays			

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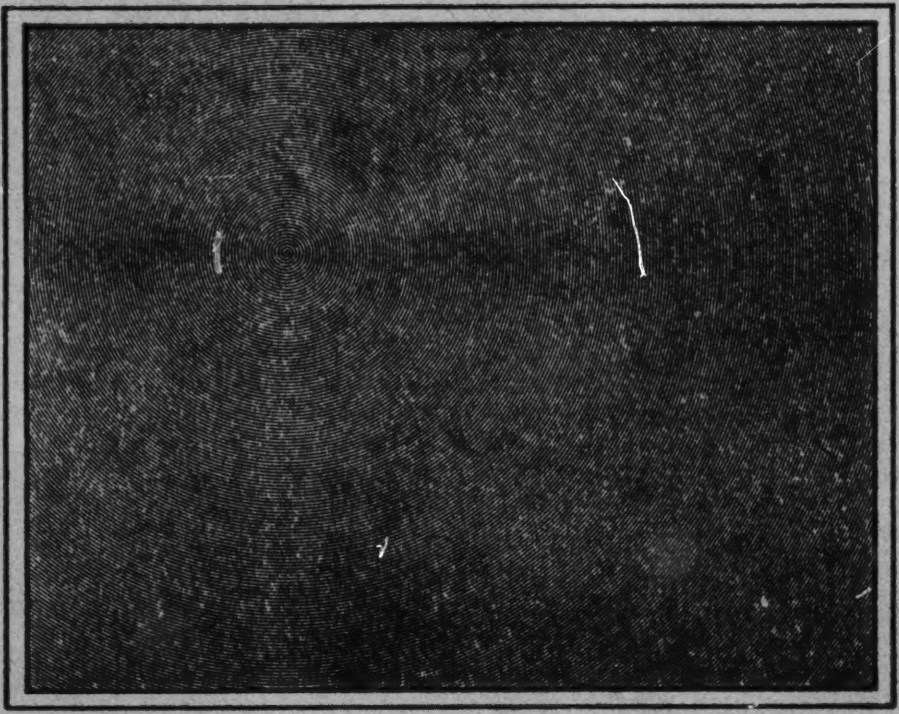
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 1

INVERSE SQUARE LAW
SPREADING OF LIGHT



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

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OCT 1979

INTRODUCTION

A reader, needing more light, moves closer to the light source. On cold nights, a camper sits closer to the fire. Faint sounds are heard more easily by placing the ear near the source of the sound. These are examples of the inverse-square law of radiation. All radiation moves outward from its source radially in straight lines. Thus, energy of radiation spreads over an ever-increasing area as it travels farther from the source.

This module presents the inverse-square law as it applies to radiant energy (light). Measurements made on an optical system in the laboratory will be used to verify the inverse-square law.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Irradiance.
  Solid angle.
  Radiant intensity.

- Write the equation for the inverse-square law of light and define each term in the equation.

- Given any two of the following quantities, calculate the third:

  Radiant intensity of a point source of light.
  Distance from light source to point of observation.
  Irradiance at point of observation.

- Given proper equipment, measure the irradiance produced by a point source of light at several distances from the source. Draw a graph of irradiance versus distance and calculate the radiant intensity of the source.

DISCUSSION

All radiation spreads as it leaves its point source. The discussion of the inverse-square law presented in this module is based upon light radiation, although the same principle and equations apply to radio waves, sound, nuclear radiation and all other types of radiation.

Figure 1 shows light radiating from a point source. The light emitted into the volume bounded by the four lines (A, B, C and D of the figure) continues to travel outward. At distance d this light energy passes through the cross-sectional area A. At 2d, the same energy spreads to cover area 4A. At 3d, it covers 9A. Figure 1 demonstrates that the area through which energy passes increases with the square of the distance from the source. This rate of increase forms the basis of the inverse-square law.

Before a detailed discussion of the inverse-square law can be presented, several concepts used in the measurement of light must be introduced. The first of these is irradiance, a measure of the power-per-unit area striking a surface. It is the power divided by area, or power-per-unit area, as given in Equation 1.

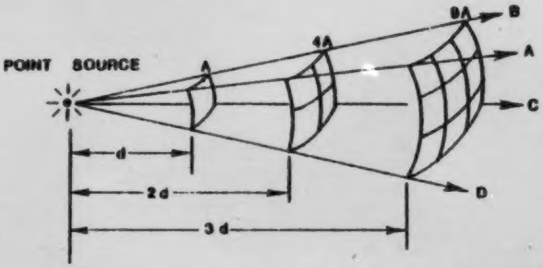


FIG. 1

$$E = \frac{P}{A} \qquad (1)$$

where

E = irradiance.

P = power.

A = area.

Example A illustrates the use of this equation in solving a problem.

EXAMPLE A: IRRADIANCE ON A SURFACE

Given: 25W (watts) of light falls on one side of a square of 0.5 meter on each side.

Find: Irradiance at surface.

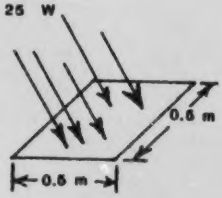
Solution:

$$A = d^2 = (0.5\ \text{m})^2$$

$$= 0.25\ \text{m}^2$$

$$E = \frac{P}{A} = \frac{25\ \text{W}}{0.25\ \text{m}^2}$$

$$= 100\ \text{watt/meter}^2$$



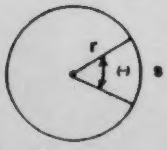
Note that the units of irradiance are "power divided by area," usually expressed in W/m^2 or W/cm^2.

The second concept to be considered is the solid angle illustrated in Figure 2. In plane geometry (Figure 2a), an angle is defined as "that part of the plane lying between two lines that meet at a point." Such an angle may be measured in degress or radians, where 2π radians equals 360 degrees. The angle in radians is defined by Equation 2.

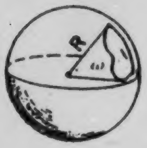
$$\theta = \frac{s}{r} \qquad (2)$$

where

θ = angle in radians.
s = length of arc subtended by angle θ.
r = radius of circle.



(A) PLANE ANGLE



(B) SOLID ANGLE

FIG. 2

Figure 2b shows the analogy in solid geometry. Solid angle, ω, is defined as "the area subtended at a spherical surface divided by the square of the radius of the sphere," as given in Equation 3.

$$\Omega = \frac{A}{R^2} \qquad (3)$$

where

Ω = solid angle in steradians.
A = area of sphere subtended by angle Ω.
R = radius of sphere.

Solid angles are measured in steradians (sr). Like the radian, the steradian is a dimensionless unit. There are 4π steradians in a complete sphere. Example B illustrates Equation 3.

EXAMPLE B: CALCULATION OF SOLID ANGLE

Given: A circular surface 10 cm in diameter, viewed from a distance of 1 m.

Find: Solid angle subtended by the surface at the eye.

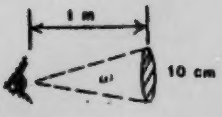
Solution:

$$A = \pi r^2 = (3.14) \times (5\text{ cm})^2$$

$$= 78.5\text{ cm}^2$$

$$\Omega = \frac{A}{R^2} = \frac{78.5\text{ cm}^2}{(100\text{ cm})^2}$$

$$\Omega = 0.00785\text{ sr}$$



Note: The circular surface has been assumed to be approximately equal to the spherical surface subtended by Ω with radius of 1 m.

The concept of a solid angle is useful in describing the way light is radiated from a source. Figure 3 shows the beam from a flashlight. At distance R, the beam illuminates area A with power P. The solid angle of the beam is very nearly given by $\omega = A/R^2$. The radiant intensity of a light source is defined as the "power-per-unit solid angle radiated by the source," as given by Equation 4.

$$I = \frac{P}{\Omega} \qquad (4)$$

where

I = radiant intensity.
P = power.
Ω = solid angle.

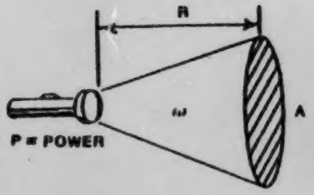


FIG. 3

Example C demonstrates the use of this equation in solving a problem.

EXAMPLE C: RADIANT INTENSITY OF A LIGHT SOURCE

Given: In Figure 3, the flashlight produces 10 W of optical power, $R = 2$ m and $A = 0.5\ \text{m}^2$.

Find: Radiant intensity of flashlight.

Solution:

$$\Omega = \frac{A}{R^2} = \frac{0.5\ \text{m}^2}{(2\ \text{m})^2}$$

$$= 0.125\ \text{sr}$$

$$I = \frac{P}{\Omega} = \frac{10\ \text{W}}{0.125\ \text{sr}}$$

$$I = 80\ \frac{\text{W}}{\text{sr}}$$

Note: radiant intensity is the function of a light source; it does not depend upon the distance from a source. For instance, if I (in Example C) is recalculated for R = 4m, Ω is shown to remain unchanged; therefore, radiant intensity I remains unchanged.

On the other hand, irradiance depends upon source-to-surface distance and decreases as distance from source increases. Irradiance, at any distance, R, from a point source of total power, P, is given by the inverse-square law (Equation 5).

$$E = \frac{P}{4\pi R^2} \qquad (5)$$

where

E = irradiance of a surface a distance R from a point source.
P = total power of point source.
R = distance from point source to surface (point of measurement).

Example D illustrates use of the inverse-square law in solving a problem.

EXAMPLE D: IRRADIANCE E AT DISTANCE R FROM POINT SOURCE

Given: A 500 W electrical arc, treated as a point source, emitting light equally in all directions.

Find: Irradiance at (a) 25 cm, (b) 50 cm and (c) 1 m.

Solution:

(a) $$E_a = \frac{P}{4\pi R^2} = \frac{500\ \text{W}}{(4) \times (3.14) \times (25\ \text{cm})^2}$$

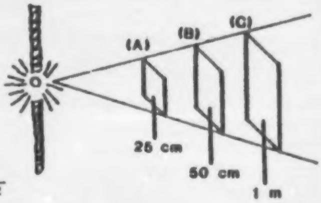
$$E_a = 6.37 \times 10^{-2}\ \frac{\text{W}}{\text{cm}^2}$$

(b) $$E_b = \frac{500\ \text{W}}{(4) \times (3.14) \times (50\ \text{cm})^2}$$

$$E_b = 1.59 \times 10^{-2}\ \frac{\text{W}}{\text{cm}^2}$$

(c) $$E_c = \frac{500\ \text{W}}{(4) \times (3.14) \times (100\ \text{cm})^2}$$

$$E_c = 3.98 \times 10^{-3}\ \frac{\text{W}}{\text{cm}^2}$$



Note: Multiplying distance by 4 (from 25 cm to 100 cm) reduces irradiance by a factor of 16 or 4^2.

Equation 6 presents an alterate form of the inverse-square law.

$$E = \frac{I}{R^2} \tag{6}$$

where

E = irradiance due to a point source.
I = radiant intensity of the point source.
R = distance from source to point of measurement.

This equation combines Equations 4 and 5.

Examples E and F provide some practice in the use of this equation in solving problems.

EXAMPLE E: IRRADIANCE CALCULATION

Given: Light source with radiant intensity of 250 W/sr.

Find: Irradiance at 10 m.

Solution:

$$E = \frac{I}{R^2}$$

$$= (250\ \text{W/sr}) \div (10\ \text{m})^2$$

$$E = 2.5\ \text{W/m}^2$$

Note: In Example E the unit "steradian" (sr) is dropped from the calculation; as noted previously, a steradian represents a ratio and, therefore, has no dimensions.

EXAMPLE F: RADIANT INTENSITY CALCULATION

Given: At a distance of 2 m from a source, 3.6 mW falls on an area of 0.5 cm^2.

Find: Radiant intensity of source.

Solution: (Use Equation 6).

$$\text{(a)}\quad E = \frac{P}{A} = \frac{3.6 \times 10^{-3}\ \text{W}}{0.5\ \text{cm}^2}$$

$$= 7.2 \times 10^{-3}\ \text{W/cm}^2$$

$$I = ER^2 = (7.2 \times 10^{-3}\ \text{W/cm}^2)(200\ \text{cm})^2$$

$$= 288\ \text{W/sr}$$

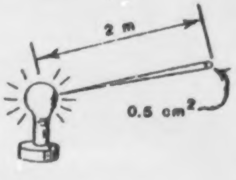
(Use Equation 4).

$$\text{(b)}\quad \Omega = \frac{A}{R^2} = \frac{0.5\ \text{cm}^2}{(200\ \text{cm})^2}$$

$$= 1.25 \times 10^{-5}\ \text{sr}$$

$$I = \frac{P}{\Omega} = \frac{3.6 \times 10^{-3}\ \text{W}}{1.25 \times 10^{-5}\ \text{sr}}$$

$$= 288\ \text{W/sr}$$



SUMMARY

Two quantities (irradiance and radiant intensity) are of major importance in describing the distribution of light energy as it travels from a light source and strikes a surface. Irradiance is a measure of the power-per-unit area striking a surface. Radiant intensity is a measure of the power-per-solid-angle leaving a source. The inverse-square law describes the rate of decrease in irradiance as the distance from the source increases. If the distance is doubled, the irradiance drops by a factor of four (2^2). If the distance is tripled, the irradiance drops by a factor of nine (3^2), and so on. This relationship applies to all forms of radiation.

DEMONSTRATION OF THE INVERSE SQUARE LAW

MATERIALS

Clear incandescent bulb, 10 W or less (flashlight with reflector removed will work).
Optical power meter.
Meter stick.

PROCEDURE

1. If power meter has a limiting aperture, remove it to allow entire detector area to be illuminated.

2. Measure dimesion of detector surface; record in Data Table.

3. Place light bulb and detector as shown in Figure 4 so that bulb filament and detector surface are at the same height and are 10 cm apart.

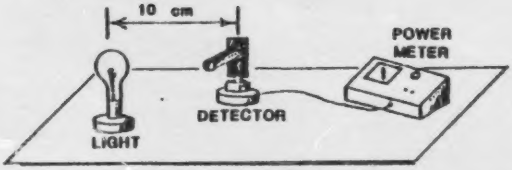


FIG. 4

4. Set power meter to least sensitive scale; turn on power meter and incandescent bulb; measure power and record in Data Table. Change power meter to more sensitive scale, if necessary, but do not drive needle past full-scale reading.

5. Move detector away from source, in 10 cm steps, to 1 m; measure and record power at each distance. Change power meter to more sensitive scale as necessary.

6. Calculate irradiance at each distance (divide power in milliwatts received by detector area in square centimenters).

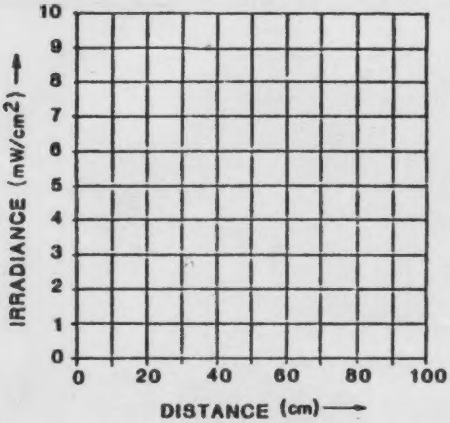
7. Calculate radiant intensity as measured from each distance (use Equation 6).

8. Plot irradiance-versus-distance on graph paper provided.

9. Explain how graph illustrates inverse-square law of light.

DATA TABLE		
Distance (cm)	Irradiance at Detector $(\frac{mW}{cm^2})$	Radiant Intensity of Light Bulb (W/sr)
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

Detector area = ____ cm^2



SELF CHECK

1. Define:

   Irradiance.
   Solid angle.
   Radiant intensity.

2. Write equation for inverse-square law of light; define each term in equation.

3. If radiant intensity of a flashlight is 5 W/sr, calculate its irradiance at 25 m.

4. If radiant intensity of an arc lamp is 150 W/sr and irradiance at a detector is 0.25 mW/cm^2, calculate distance from light source to detector.

5. If irradiance 15 m from a light source is 0.03 mW/cm^2, calculate irradiance at 20 m.

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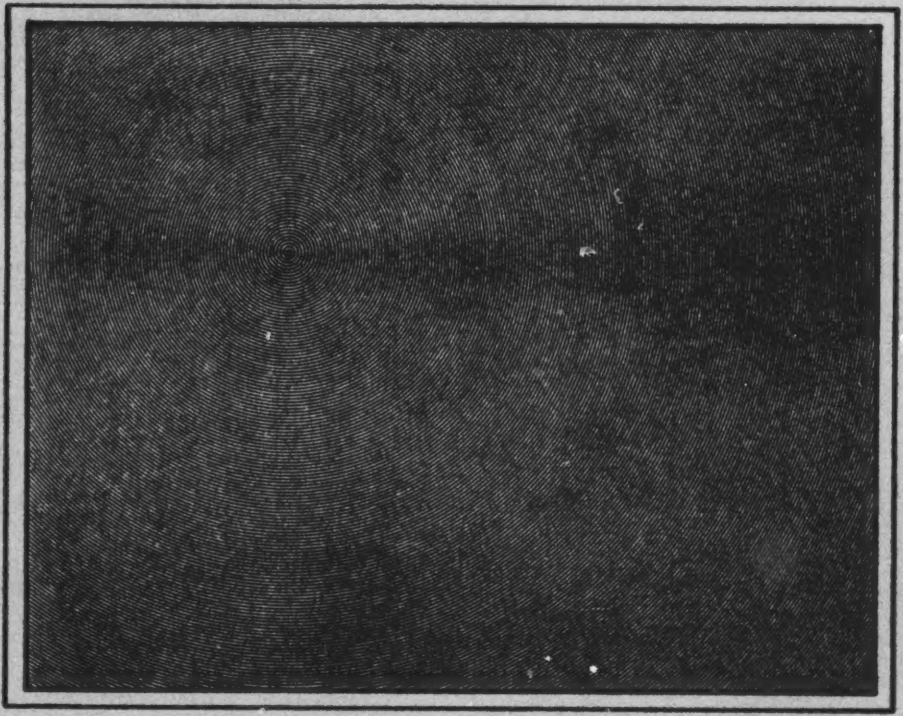
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 2

THE OPTICAL SPECTRUM



LIGHT APPLICATION OF RADIATION

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INTRODUCTION

The term "optics" is often thought of as referring to devices used within the visible portion of the electromagnetic spectrum. Optics and optical instruments are actually employed over a broad spectral range, including not only visible light radiation, but also the adjacent ultraviolet and infrared. The optical spectrum portion is the more important one to us biologically, providing heat, energy for photosynthesis, and the basis for sight itself. This module presents the basic properties and several applications which involve the optical portion of the electromagnetic spectrum. In the laboratory the student will utilize diffraction grating to examine the visible spectrum.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Label the infrared, visible and ultraviolet portions of the electromagnetic spectrum; supply the wavelength and frequency scales, given a blank chart of the optical spectrum.
- Define the following wavelength units:

  Micron.
  Nanometer.
  Angstrom.

- Given one of the following quantities for a photon, calculate the other two:

  Wavelength.
  Frequency.
  Energy.

- Explain briefly the origin of each of the following types of spectra:

  Line.
  Band.
  Continuous.

- State one application of each of the following regions of the optical spectrum:

  Visible.
  Ultraviolet.
  Infrared.

- Given the appropriate equipment, measure the wavelengths of several lines in a line spectrum.

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THE OPTICAL SPECTRUM

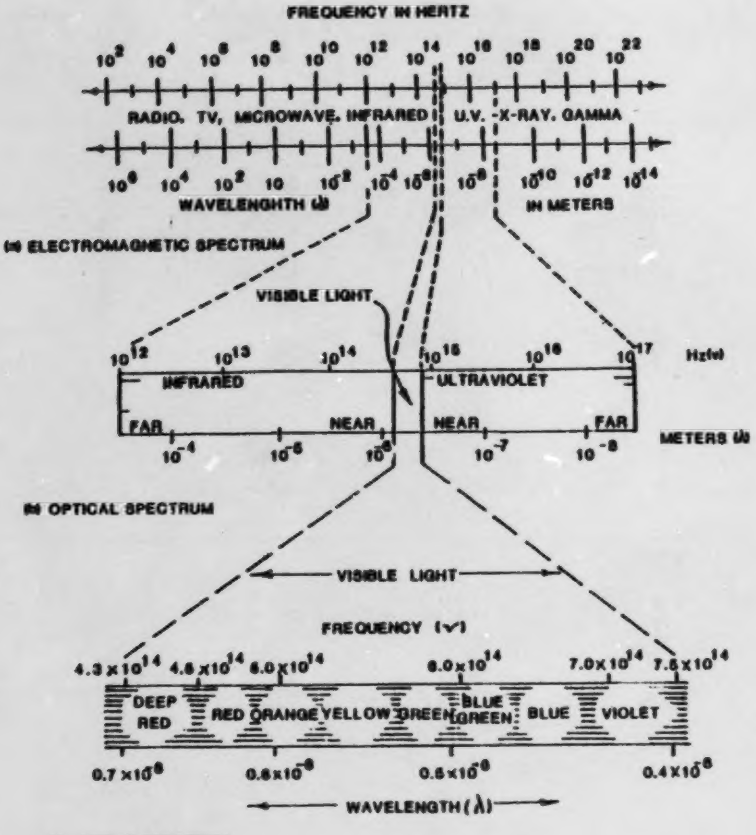

FREQUENCY IN HERTZ
10^2 10^4 10^6 10^8 10^10 10^12 10^14 10^16 10^18 10^20 10^22
RADIO, TV, MICROWAVE, INFRARED | U.V. -X-RAY, GAMMA
10^6 10^4 10^2 10 10^-2 10^-4 10^-6 10^-8 10^-10 10^-12 10^-14
WAVELENGHTH (λ) IN METERS
(a) ELECTROMAGNETIC SPECTRUM
VISIBLE LIGHT
10^12 10^13 10^14 10^15 10^16 10^17 Hz(ν)
INFRARED
ULTRAVIOLET
FAR NEAR NEAR FAR
10^-4 10^-5 10^-6 10^-7 10^-8 METERS (λ)
(b) OPTICAL SPECTRUM
VISIBLE LIGHT
FREQUENCY (ν)
4.3 x 10^14 4.8 x 10^14 5.0 x 10^14 6.0 x 10^14 7.0 x 10^14 7.5 x 10^14
DEEP RED
RED
ORANGE
YELLOW
GREEN
BLUE GREEN
BLUE
VIOLET
0.7 x 10^-6 0.6 x 10^-6 0.5 x 10^-6 0.4 x 10^-6
WAVELENGTH (λ)
(c) VISIBLE SPECTRUM

FIG. 1

Figure 1a shows the electromagnetic spectrum and the location of the optical spectrum. The obtical spectrum (Figure 1b) is composed of visible light, the longer-wavelength infrared (IR) light and the shorter-wavelength ultraviolet (UV) light. The wavelength range of most interest in this module is the visible spectrum (Figure 1c) and those wavelengths closest to the visible - called the near-infrared and the near-ultraviolet.

Table I lists three distance units commonly used to express the wavelengths in the optical spectrum. Angstroms (10^{-10} m) are normally used for the far ultraviolet, for X-rays, and sometimes for the near ultraviolet and visible, although the nanometer (10^{-9} m) is more common for the longer wavelengths. Infrared wavelengths are usually expressed in microns (10^{-6} m). Example A shows the conversion of a wavelength given in meters into each of these units.

TABLE 1: WAVELENGTH UNITS

Name	Symbol	Definition
Angstrom	A	10^{-10} m
Nanometer	nm	10^{-9} m
Micron	μ	10^{-6} m

EXAMPLE A: CONVERSION OF WAVELENGTH UNITS

Given: The wavelength of a photon is 6.33×10^{-7} m.

Find: Wavelength in (a) angstroms, (b) nanometers and (c) microns.

Solution:

(a) $(6.33 \times 10^{-7}\ \text{m}) \times \left(\frac{10^{10}\ \text{A}}{1\ \text{m}}\right) = 6330\ \text{A}$

(b) $(6.33 \times 10^{-7}\ \text{m}) \times \left(\frac{10^{9}\ \text{nm}}{1\ \text{m}}\right) = 633\ \text{nm}$

(c) $(6.33 \times 10^{-7}\ \text{m}) \times \left(\frac{10^{6}\ \mu}{1\ \text{m}}\right) = 0.633\mu$

The frequency of a photon may be calculated by using Equation 1 if its wavelength is known.

$$f = \frac{c}{\lambda} \qquad (1)$$

where

f = frequency.
c = speed of light.
λ = wavelength.

This equation is used in solving a problem in Example B.

EXAMPLE B: FREQUENCY OF A PHOTON

Given: Wavelength of a photon is 430 nm.

Find: Frequency of the photon.

Solution:

$$f = \frac{c}{\lambda}$$

$$= \frac{3 \times 10^{8}\ \text{m/s}}{4.3 \times 10^{-7}\ \text{m}} \quad (430\ \text{nm} = 4.3 \times 10^{-7}\ \text{m.})$$

$$f = 6.98 \times 10^{14}\ \text{Hz}$$

The energy of a photon may be calculated if its frequency is known by using Equation 2.

$$E = hf \tag{2}$$

where

E = energy of photon.

h = Planck's constant of 6.625×10^{-34} J x s.

f = frequency.

This equation is used to solve a problem in Example C.

EXAMPLE C: ENERGY OF A PHOTON

Given: Frequency of a proton is 5×10^{14} Hz.

Find: Energy of the photon.

Solution: $E = hf$

$$= (6.625 \times 10^{-34}\ \text{J} \times \text{s}) \times (5 \times 10^{14}\ \text{Hz})$$

$$E = 3.31 \times 10^{-19}\ \text{J}$$

EMISSION SPECTRA

Light in the optical spectrum can be produced by several means. The most important of these sources are electronic transistions within atoms, vibrational and rotational transitions within molecules, and incandescent emission from hot materials. Each of these produce a characteristic emission spectrum.

Figure 2 shows a typical line spectrum produced by electronic transitions in atoms. Intensity of light is plotted along the vertical axis, and the wavelength of light is plotted, in microns, along the horizontal axis. Line spectra are produced when an electric current flows through a low-pressure gas. Electron collisions raise atoms to high-energy states. Each atom then returns to lower states by emitting its excess energy in the form of photons. Emission lines in this spectrum vary greatly in width and intensity, but each atomic species has its own characteristic spectrum. Line spectra occur in the near IR, visible and UV portions of the electromagnetic spectrum.

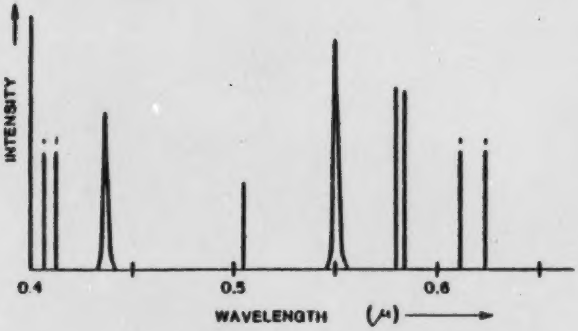


FIG. 2

Figure 3 displays a band spectrum produced by molecular transitions. Each band is actually composed of a large number of closely-spaced lines. Molecules contain energy not only in the electronic levels of their individual atoms, but also in the form of vibrational energy of the atoms and rotational energy of the entire molecule. Each band in Figure 3 is the result of a change in the vibrational energy of a molecule. Fine lines within the bands are produced by accompanying changes in rotational energy. Band spectra are produced by molecular gases such as diatomic nitrogen (N_2), by carbon dioxide (CO_2) and by some liquids and crystals. Band spectra occur throughout the optical spectrum but are most numerous in the infrared region.

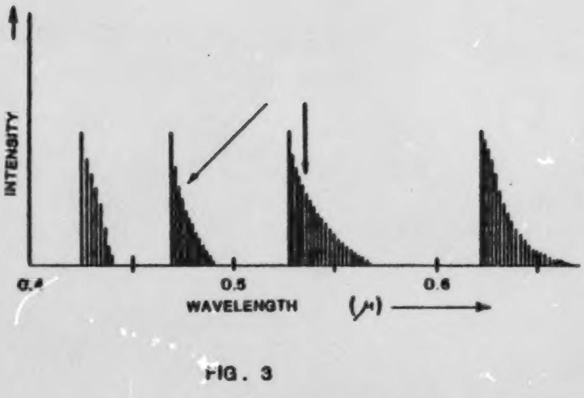


FIG. 3

Figure 4 shows a continuous spectrum emitted from a material at high temperature. Unlike line and band spectra, the continuous spectrum contains some light at all wavelengths. This light is the result of changes in the thermal energy of atoms in the material. In general, solids, liquids and high-pressure gases produce continuous spectra when heated to incandescence. Continuous spectra may be produced throughout the optical spectrum, with higher-temperature materials emitting shorter wavelengths. A more detailed discussion of this type of spectrum is contained in Module 13L3, "Light Sources."

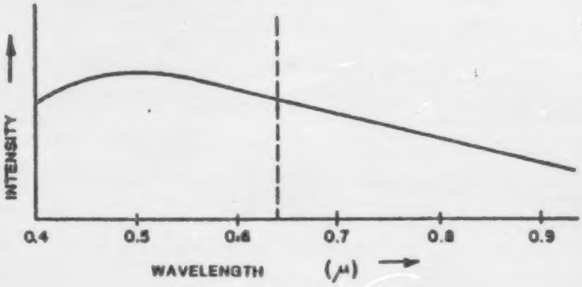


FIG. 4

APPLICATIONS OF THE OPTICAL SPECTRUM

The visible portion of the optical spectrum is the basis of human sight. All information received by the eye is carried by radiation in this portion of the spectrum. Fluorescent lights, television, photography and the candle are examples of technology applied to produce and use visible light.

The infrared portion of the spectrum cannot be detected by the eye. Instead, it is felt as heat radiation. Electrical heating devices, such as space heaters and toasters, produce heat in the form of infrared radiation. This spectral region contains much of the usable solar energy striking the earth. In recent years, a complex technology based upon infrared radiation has developed IR sensing and imaging devices used in night vision and temperature-measuring systems. Photographs are taken with special IR-sensitive film are used to evaluate insulation in buildings and to locate hot spots in mechanical and electrical devices. Infrared technology is rapidly becoming a valuable tool in energy conservation and utilization.

Ultraviolet light, often referred to as black light, is also invisible. It is the component of sunlight that is responsible for suntans. Many materials absorb UV light and re-emit its energy in the form of visible light (longer wavelengths and less energy per photon). This process, called fluorescence, has many medical applications, and is used to locate leaks in fluid systems. Laundry detergents make clothes "whiter than white" because they leave a fluorescent residue that absorbs the UV in sunlight and re-emits the energy as visible light.

SUMMARY

The optical spectrum of light radiation includes both visible light and invisible light (ultraviolet and infrared). Light in the optical spectrum is produced by electronic transitions within atoms, by vibrational and rotational transitions within molecules and by incandescent emissions from hot materials. Each of these three sources produce, respectively, a characteristic emission spectrum that can be represented graphically as line, band or continuous.

LABORATORY

DEMOSTRATION OF DIFFRACTION GRATING

MATERIALS

Grating spectroscope.
Incandescent light bulb.
Spectrum tubes: helium, neon, carbon dioxide, water vapor.
Power supply for spectrum tubes.

PROCEDURE

The grating spectroscope is a device that separates light into its component colors and displays them against a calibrated scale for wavelength measurement. A detailed discussion of the principles involved is presented in Module 13L12, "Diffraction Grating - Measuring the Wavelengths of Light."

1. Turn on incandescent bulb. Place slit of spectroscope near bulb; look into eyepiece of spectroscope (Figure 5). Observe continuous visible spectrum; sketch and describe it in Data Table.

2. Replace incandescent source with helium spectrum tube and power supply (Figure 6). Caution: Power supply produces high voltage. Always turn off power supply before handling spectrum tubes. Also allow tubes to cool before removal, to avoid burn or breakage.

3. Turn on spectrum tube power supply. Position spectroscope with slit vertical near capillary portion of tube. Observe line spectrum of helium; sketch and describe it in Data Table.

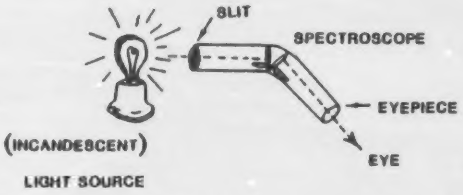
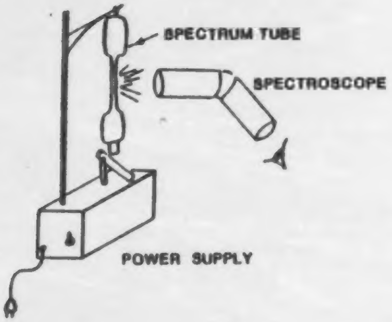


FIG. 5



4. Replace helim tube with neon tube, follow appropriate precautions. Observe, sketch and describe line spectrum.

5. Replace neon tube with carbon dioxide tube. Observe and describe band spectrum of carbon dioxide.

6. Replace carbon dioxide tube with water vapor tube. Observe, sketch and describe spectrum.

7. Replace helium tube in holder of power supply. Measure wavelengths of three strong lines; record in Data Table.

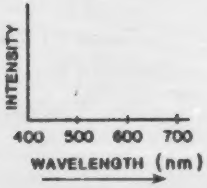
8. Use Equations 1 and 2 to calculate frequency and energy per photon of helium lines.

9. How do the sketches of each spectrum compare with those in the Discussion?

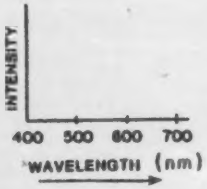
DATA TABLE

Description of Spectra:

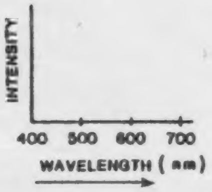
Incandescent lamp:



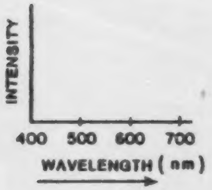
Helium:



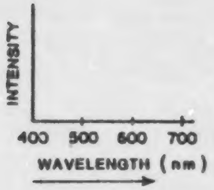
Neon:



Carbon dioxide:



Water vapor:

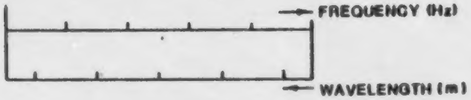


Helium lines:

Color	Wavelength (nm)	Frequency (Hz)	Energy of Photon (J)

SELF CHECK

1. On the following chart, label visible, IR and UV portions of the spectrum. Complete the wavelength and frequency scales by adding numerical values to the points given.



2. Define the following wavelength units:

   Micron.
   Nanometer.
   Angstrom.

3. Make the necessary calculations of energy, frequency and wavelength to complete the following chart.

Color	Energy of Photon (J)	Frequency (Hz)	Wavelength (nm)
Red			650
Green		5.78×10^{14}	
Blue	4.73×10^{-19}		

4. Explain briefly the origin of each of the following:

   Line spectra.
   Band spectra.
   Continuous spectra.

5. State an application of each of the following:

   Visible light.
   UV light.
   IR light.

REFERENCE

Jenkins, Francis A. and White, Harvey E. Fundamentals of Optics. 3rd. ed. New York: McGraw-Hill Book Company, 1957.

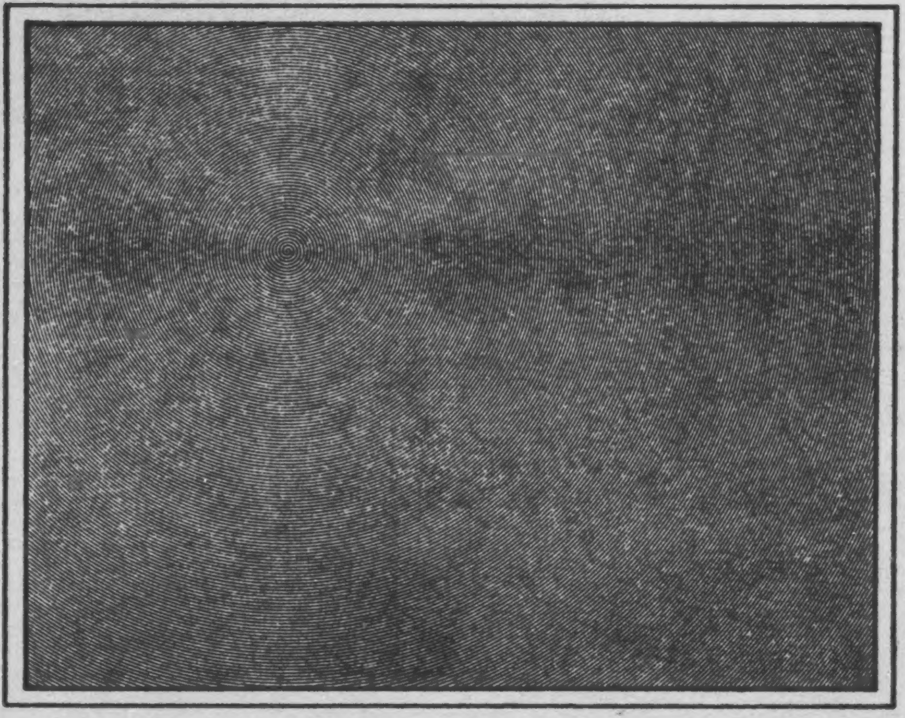
Technical Education Research Center - Southwest, ed. "Wave Properties of Light." Module 1-3, Laser/Electro-Optics Series. Waco, TX: TERC-SW, 1976.

________. "Sources and Their Characteristics." Module 5-1, Laser/Electro-Optics Series. Waco, TX: TERC-SW, 1976.

UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 3
LIGHT SOURCES



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Man has always needed light. Artificial production of light was one of the first technological accomplishments. Today it is essential to every part of modern civilization. This module will discuss the operation of several common devices for producing visible electromagnetic radiation. In the laboratory, the student will examine light from incandescent and fluorescent sources.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation," Application Modules: 13L1, "Inverse-Square Law - Spreading of Light," and 13L2, "The Optical Spectrum."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Graph approximately the relative response of the human eye as a function of the wavelength of light.
- Describe the process by which light is produced and the output spectrum of the following light sources.

  Incandescent bulb.
  Fluorescent bulb.
  Metal vapor lamp.
- Draw three curves to approximate position in a single graph, showing "relative output" of a blackbody radiator at 3000°K, at 4000°K and at 5000°K as functions of wavelength.
- Describe and give an example of a point source and an extended source of light.
- Given appropriate equipment, observe and describe the output spectrum and irradiance pattern of incandescent and fluorescent sources.

RESPONSE OF THE HUMAN EYE

Figure 1 shows the relative response of the human eye to light of various wavelengths. The eye is most sensitive to yellow light with a wavelength of 55 nm (nanometers). The response drops off rather sharply on each side of this value, reaching zero at 400 nm, the edge of the ultraviolet region, and at 700 nm, the edge of the infrared region. Visible light sources are devices that produce radiation in the region of the electromagnetic spectrum limited to the range of 400 nm - 700 nm.

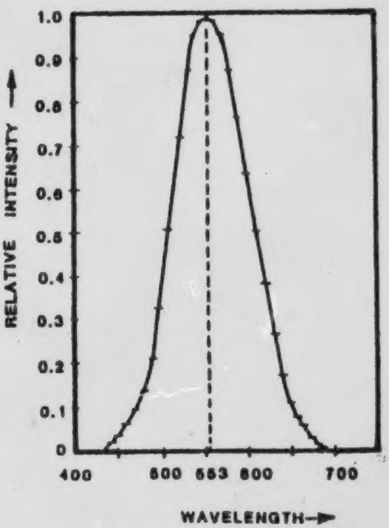


FIG. 1

EMISSION OF LIGHT BY COMMON SOURCES

Figure 2 illustrates an ordinary incandescent bulb. It consists of a thin filament of tungsten wire sealed inside a glass bulb envelope. The glass bulb is either evacuated or filled with an inert gas. When a current flows through the filament, it is heated to incandescence. Atoms in the filament are bound to fixed positions, but are free to vibrate around those positions. As this vibration (heat energy) occurs, neighboring atoms collide with one another violently. During these collisons, the atoms decelerate, and a portion of their vibrational energy is converted to electromagnetic radiation in the infrared, visible or near-ultraviolet portions of the spectrum. The result is a continuous spectrum (Figure 3).

Figure 3 shows the relative intensity produced by an incandescent source as a function of wavelength at three different temperatures. These curves are called blackbody radiation curves and are based upon the theoretical emission from a perfect radiator (blackbody). Although practical incandescent sources do not emit as much light as a perfect blackbody radiator would at the same temperature, the spectral distribution of the light produced is the same. Notice that in Figure 3 an increase in temperature increases the intensity of light produced at all wavelengths. Note also that raising the temperature causes the peak of the emission curve to move toward the shorter wavelengths.

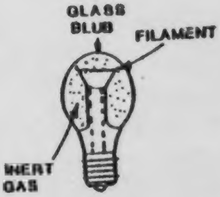


FIG. 2

The curves in Figure 3 also reveal the inefficiency of incandescent light sources. Only that fraction of the output that falls in the visible region is useful for human vision. Most of the energy used to heat an incandescent source results in production of unneeded ultraviolet and infrared

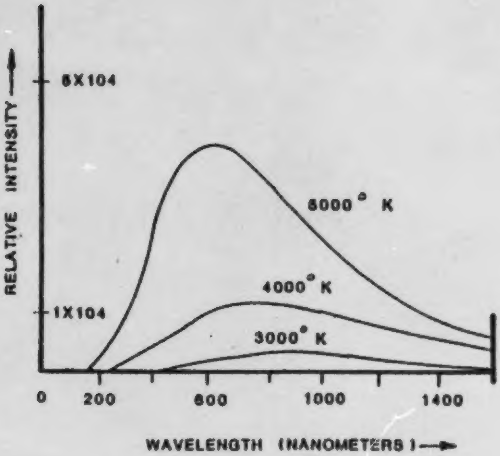


FIG. 3

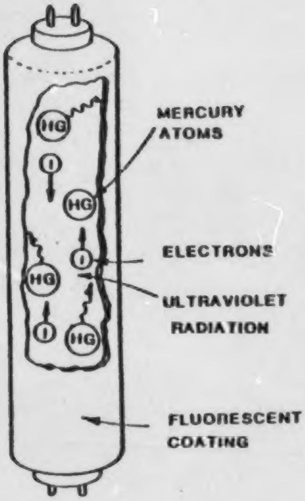

HG
HG
HG
HG
MERCURY ATOMS
ELECTRONS
ULTRAVIOLET RADIATION
FLUORESCENT COATING

FIG. 4

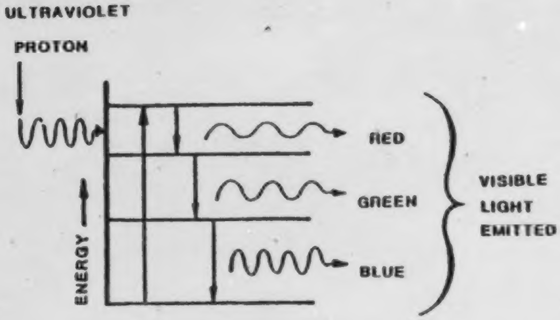

ULTRAVIOLET PROTON
ENERGY
RED
GREEN
BLUE
VISIBLE LIGHT EMITTED

FIG. 5

radiation.

Figure 4 shows the operation of a fluorescent lamp. This lamp consists of a glass tube containing mercury vapor at low pressure. The inner surface of the tube is coated with fluorescent material. Alternating current is conducted through the tube by free electrons. When one of these electrons collides with a mercury atom, part of its energy is transferred to the atom, placing it in an excited energy state. The mercury atom usually emits this energy in the form of a photon in the ultraviolet range, although some visible photons also may be produced. Ultraviolet photons strike atoms in the fluorescent coating of the tube and are absorbed, raising these atoms, in turn, to higher energy levels. These atoms release their energy in several steps, producing visible light, as shown schematically by the energy level diagram in Figure 5. The process is called fluorescence.

Several fluorescent substances may be used, and by proper selection and blending, can result in light of any desired color. Most fluorescent bulbs produce a continuous spectrum in the visible region. Their outputs also contain the strong visible lines of the mercury spectrum at 436 nm (blue) and 546 nm (green). Unlike incandescent sources, most of the energy required to activate fluorescent bulbs emerges as visible light, making them more efficient.

A third type of lighting, is the metal vapor lamp, which is important for large areas or for outdoor lighting. A number of metals that vaporize easily may be used, but mercury and sodium are more efficient than most others. In this lamp, a high pressure metal vapor is heated to incandescence. This produces the same line spectrum as an incandescent source. Mercury vapor lamps appear bluish because of the strong blue and green lines in the mercury spectrum. Sodium lamps are yellowish because of a pair of strong emission lines at 589 nm. Because this wavelength is near the peak of the response curve of the human eye, sodium vapor lamps produce usable light with greater efficiency than any other high-intensity source.

SIZE OF LIGHT SOURCES

Another important characteristic of any light source is its size. A point source of light is a source that emits all its radiant energy from a single point. Such an ideal source does not exist, although any source whose largest dimension is small compared with distance to the observer may be treated as a point source. Thus, a single incandescent bulb in a large room approximates a point source (Figure 6). This type of lighting produces well-defined shadows, and the light source may appear uncomfortably bright when viewed directly.

An extended source (Figure 7) is any light source whose dimensions are significant when compared with the distance to the observer. Because light from an extended source emerges from a large area, the source does not appear uncomfortably bright when viewed directly. The shadows produced do not have well-defined boundaries, since light strikes objects from many directions. For these reasons, extended sources are preferred for most illumination applications. Lamp shades and home lighting fixtures for incandescent bulbs are examples of devices that change point sources into extended sources.

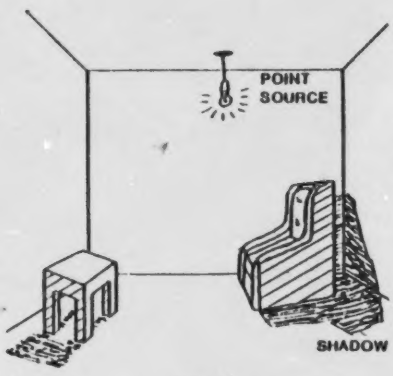


FIG. 6

SUMMARY

Visible light sources produce electromagnetic radiation in the visible range 400 nm - 700 nm. Common emitters of visible light are the incandescent bulb (a bulb, tungsten filament, and inert gas), the fluorescent tube, (a fluorescent-coated tube containing mercury vapor) and the metal vapor lamp (a bulb of mercury of sodium vapor heated to incandescence). In size a light source is either a point source that produces well-defined shadows, or an extended source over a large area with shadows of less contrast.

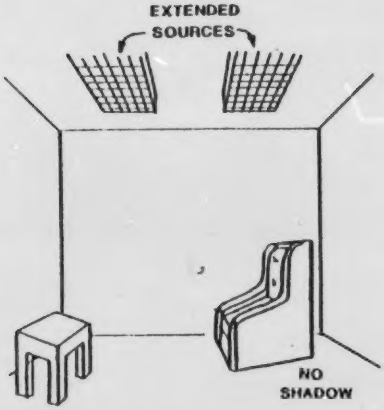


FIG. 7

ISO-IRRADIANCE PLOT

MATERIALS

Clear incandescent bulb, 15 W or less, with socket and power cord.
Fluorescent bulb with support and electrical components.
Two large sheets of white paper (approximately 2 x 3 feet).
Optical power meter.

PROCEDURES

1. Set incandescent bulb on one edge of a large sheet of paper (Figure 8). Mark position of point source.

2. Set power meter detector about 20 cm from light source and at same height as source. Measure irradiance (power/area); record reading. Mark position of detector.

3. Move power meter detector to new position at approximately same distance from bulb. Position radially to obtain same irradiance value. Mark position of detector.

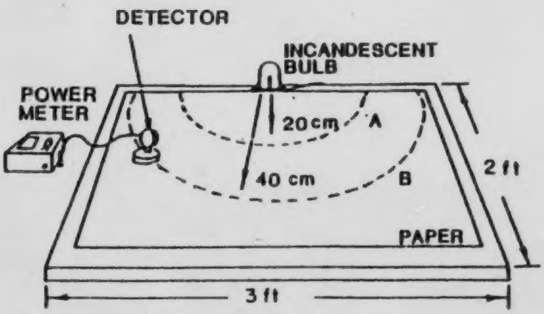


FIG. 8

4. Continue this process circumferentiatlly around light until ten points are marked. Connect all marks with a smooth line. (This line, line A in Figure 8, is called an iso-irradiance curve, since irradiance is the same at all points on it.)

5. Repeat steps 1-4 with a starting distance of 40 cm to draw curve B of Figure 8.

6. Refer to Figure 9. Set fluorescent bulb on one edge of a large sheet of paper. Mark position of bulb.

7. Repeat steps 1-6 above for fluorescent bulb. At each measurement point, power meter detector should be oriented to read maximum irradiance.

8. Sketch and describe in Data Table iso-irradiance plots of two light sources.

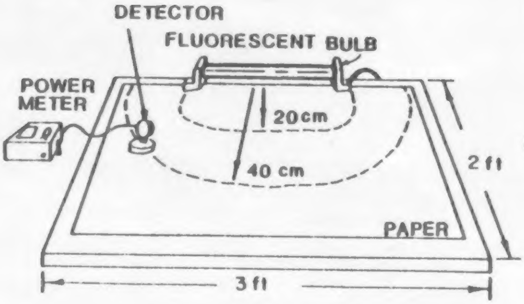

DETECTOR
FLUORESCENT BULB
POWER METER
20cm
40 cm
2 ft
PAPER
3 ft

FIG. 9

SPECTRAL OUTPUT

MATERIALS

Clear incandescent bulb, 15 W or less, with socket and power cord.
Fluorescent bulb with support and electrical components.
Variable auto-transformer 0 to 125 V a.c.
Grating spectroscope.

PROCEDURE

1. Plug incandescent lamp into variable auto-transformer output. Set auto-transformer for maximum output. Set up spectroscope to view spectrum (Figure 10). Do not move spectroscope.

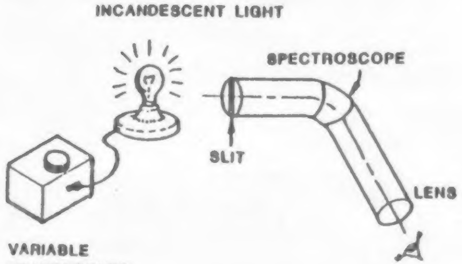

INCANDESCENT LIGHT
SPECTROSCOPE
SLIT
LENS
VARIABLE TRANSFORMER
EYE

FIG. 10

2. Turn off room lights. Set auto-transformer output to zero.

3. Observe spectrum of incandescent bulb as output voltage of auto-transformer is slowly increased. Note when various colors appear. Describe in Data Table.

4. Replace incandescent lamp (and auto-transformer) with fluo-

cent lamp.

5. Turn on fluorescent bulb. Observe and describe spectrum.

DATA TABLE

1. Iso-irradiance plot.

Irradiance: 20 cm from incandescent bulb, E_1 = ____ mW/cm^2
40 cm from incandescent bulb, E_2 = ____ mW/cm^2
20 cm from fluorescent bulb, E_3 = ____ mW/cm^2
40 cm from fluorescent bulb, E_4 = ____ mW/cm^2

Sketch and describe iso-irradiance plots for:

Incandescent bulb. Fluorescent bulb.

2. Spectral output.

Describe how spectral output of incandescent lamp changed as voltage was increased.

Describe spectral output of fluorescent lamp.

SELF CHECK

1. List each of the following wavelengths of light:

   Shortest seen by human eye.
   Longest seen by human eye.
   Peak of human visual response curve.

2. Describe the process of producing visible light in each of the following:

   Incandescent bulb.
   Fluorescent bulb.
   Metal vapor lamp.

3. How does the output spectrum of a blackbody change as its temperature increases?

4. Identify each of the following as a point source or an extended source:

   Incandescent bulb viewed from five feet.
   Incandescent bulb viewed from fifty feet.
   Television screen.
   Star.

REFERENCES

Technical Education Research Center - Southwest, ed. "Sources and Their Characteristics." Module 5-1, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

Technical Education Research Center - Southwest, ed. "Radiometry and Photometry." Module 5-2, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

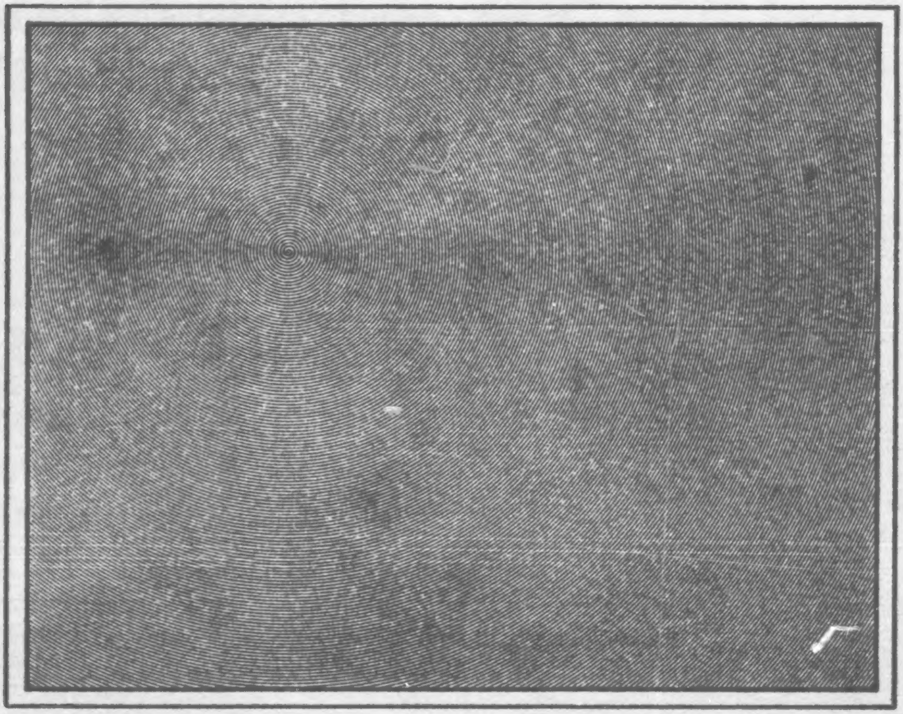
The Way Things Work, An Illustrated Encyclopedia of Technology. New York: Simon and Schuster Publishing Company, 1967.

UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 4

LASERS



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

The laser is a source of unique light radiation, with a wide variety of applications. Laser light is used to drill holes in diamonds, to weld steel accurately, to measure large distances (for example, to the moon), to repair detached retinas and to accomplish many other applications. The laser is one of the more versatile tools of modern technology. This module will discuss the properties of laser light, the basic theory of operation of the laser and a number of important laser applications. In the laboratory the student will learn how to operate a low-power, helium-neon laser.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following properties of laser light:

  Monochromaticity.
  Directionality.
  Coherence.

- Describe the process of stimulated emission.
- State the purpose of the important elements of a laser.
- List several important applications of the laser.
- List all safety precautions necessary for safe operation of low-power, helium-neon laser; describe why each is important.
- Operate a low-power, helium-neon laser safely.

PROPERTIES OF LASER LIGHT

Light emitted by lasers is uniquely different from that produced by ordinary light souces, such as incandescent or fluorescent bulbs. All laser applications depend upon one or more of the unique properties of laser light.

Common light sources produce light that contains many different colors (different frequencies and wavelengths). Laser light is composed very nearly of only one wavelength. This property is called monochromaticity.

Ordinary light sources emit their light in all directions (Figure 1a). Light leaves a laser in a tight beam that spreads slowly as it moves away from the laser (Figure 1b). Thus, laser light possesses high directionality.

Individual waves of light produced by ordinary sources have no fixed phase relationships (Figure 2a). However, in the case of laser light, all the waves are in step. Coherence is the property of laser light, meaning that all light waves are in phase (Figure 2b).

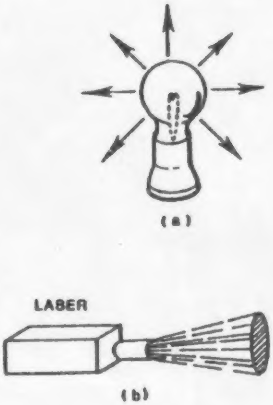


FIG. 1

STIMULATED EMISSION

The word "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. It is the process of stimulated emission that results in the unique properties of laser light.

Stimulated emission is shown schematically in Figure 3. Initially an atom is in a high-energy state E_3 represented by the solid circle in the figure. An incident photon, with an energy equal to the energy difference between this state and some lower-energy state E_2, passes near the atom. This stimulates the atom to drop to E_2, emitting the energy difference $(E_3 - E_2)$ in the form of a photon. This photon has the same wavelength as the stimulating photon (monochromaticity), travels in the same direction (directionality) and is in phase with the stimulating photon (coherence).

ELEMENTS OF A LASER

For a laser to produce enough light to be useful, the stimulated emission process must occur many times. This repetition requires that a large number of atoms must be in energy state E_3 of Figure 3 and that a number of photons of the correct wavelength must be present for stimulation of these atoms. Figure 4 shows the four essential elements necessary to meet these requirements in any laser.

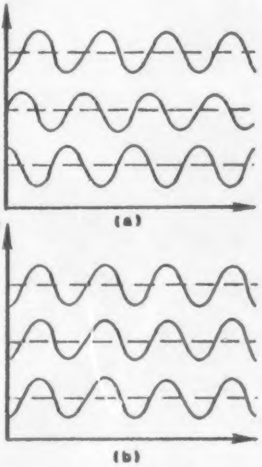


FIG. 2

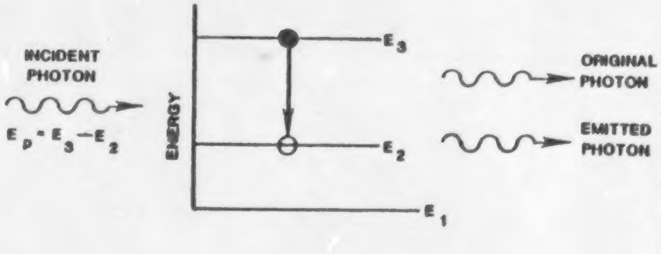

INCIDENT PHOTON
$E_p = E_3 - E_2$
ENERGY
E_3
E_2
E_1
ORIGINAL PHOTON
EMITTED PHOTON

FIG. 3

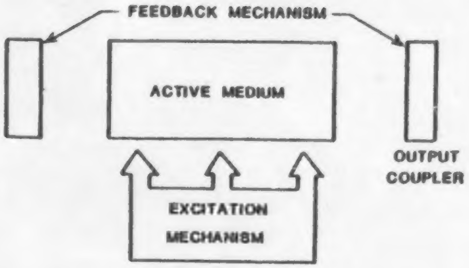

FEEDBACK MECHANISM
ACTIVE MEDIUM
OUTPUT COUPLER
EXCITATION MECHANISM

FIG. 4

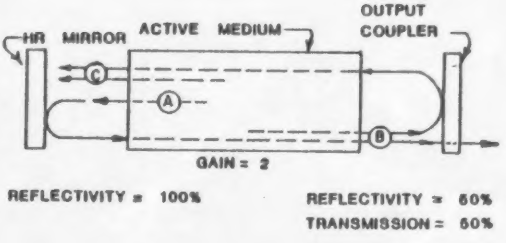

HR MIRROR
ACTIVE MEDIUM
OUTPUT COUPLER
C
A
B
GAIN = 2
REFLECTIVITY = 100%
REFLECTIVITY = 50%
TRANSMISSION = 50%

FIG. 5

The active medium is a collection of atoms or molecules that may be raised, or excited, to the proper energy level to produce light by stimulated emission. The excitation mechanism is an energy source that provides energy to the atoms, moving them to the proper energy level. This energy level is referred to as an excited state. The feedback mechanism is a pair of mirrors that reflect the coherent light produced back through the active medium to cause more stimulated emission. One of these mirrors is partially transparent and allows part of the light striking it to pass out of the laser. It is called the output coupler.

Figure 5 shows how the laser beam is produced. The output coupler of this laser is a partially-reflective mirror that reflects 50% of the laser light striking it and allows 50% to pass through to form the output beam. The other mirror is 100% reflective and is often called the high-reflectance (HR) mirror. The active medium acts as an optical amplifier with a gain of 2. The process begins at point A with the spontaneous emission of a photon traveling perpendicular to the mirror surfaces. This photon is reflected back through the active medium, where stimulated emission occurs. Two identical photons emerge in phase at point B. One passes through the output coupler to form the output beam. The other is reflected back through the active medium to produce more stimulated emission C. This process continues as long as there are enough atoms in the excited energy state to provide gain. The light produced is monochromatic, directional and coherent.

LASER CLASSIFICATION

While all lasers have the same basic elements and all operate as described above, the construction details and output characteristics vary greatly. Lasers may be classified in the following ways:

ACTIVE MEDIUM

Most common lasers use either a gas or a solid for an active medium. A gas laser (Figure 6) consists of a long, narrow tube that contains lasing gas. Mirrors are located at each end of the tube.

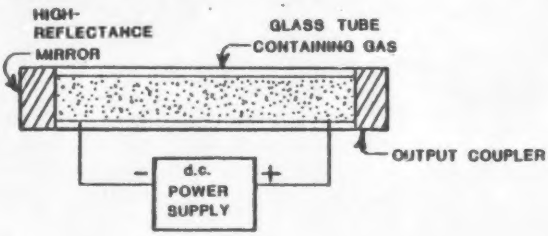

HIGH-REFLECTANCE MIRROR
GLASS TUBE CONTAINING GAS
OUTPUT COUPLER
-
d.c. POWER SUPPLY
+

FIG. 6

The active medium of a solid laser (Figure 7) consists of a cylinder of glass or of a crystal such as ruby. Mirrors may be located externally, as shown in Figure 7, or may be applied directly to the ends of the laser rod. Liquids and semiconductor materials may also be used as laser active mediums.

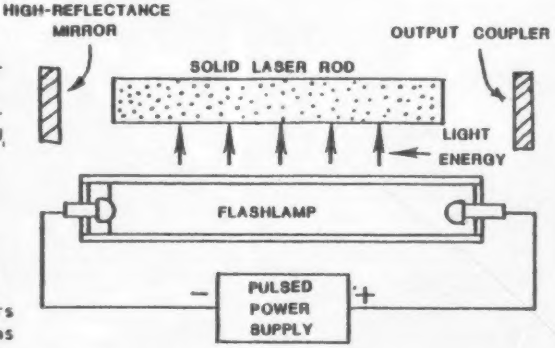

HIGH-REFLECTANCE MIRROR
OUTPUT COUPLER
SOLID LASER ROD
LIGHT ENERGY
FLASHLAMP
-
PULSED POWER SUPPLY
+

FIG. 7

EXCITATION MECHANISM

Energy is supplied to most gas lasers by passing a current through the gas (Figure 6). A few gas lasers obtain energy from chemical reactions in the gas. Solid and liquid lasers obtain energy by absorbing light from another source (Figure 7), which is called optical pumping, and may employ either a flashlamp or a continuous lamp.

OUTPUT DURATION

Continuous-wave lasers are those that produce continuous output beams. Pulsed lasers emit coherent light in short bursts. Lasers may be built to produce pulses with durations from less than a nanosecond to several milliseconds.

OUTPUT WAVELENGTH

Each laser emits a specific wavelength, but lasers may be built to produce light at almost any wavelength in the near-ultraviolet, visible and infrared portions of the spectrum.

LASER APPLICATIONS

There are many applications of lasers, and new ones are developed each year. A few of the more important applications are presented here:

- Alignment. The high directionality of light from lasers makes them ideal alignment tools. Low-power, helium-neon gas lasers are used for alignment problems throughout the industrial world, principally in construction industries.

- Materials processing. High-power, continuous, carbon dioxide gas lasers are commonly used for cutting, welding and heat treating of metals. Pulsed solid lasers are employed to drill small holes in metal parts. Lasers can drill small holes at a higher rate and with a smaller diameter than can be accomplished by any other means. A wide variety of materials, including cloth and semiconductor circuits, are cut with lasers.

- Communication. Modulated lasers are used as communication devices. A single laser beam can carry millions of telephone calls at once. Glass fibers carrying laser beams are replacing bulky, expensive cables used for telephone communication.

- Distance measurement. A laser rangefinder sends out a short pulse of light and measures the time necessary for a reflection to return. This technique is used in military applications and in surveying. Astronomical laser rangefinders have measured the distance to the moon and the altitude of satellites to within a few centimeters. Laser interferometers are used to measure short distances to within a millionth of an inch. This technique is discussed in Module 13L11, "Interference - Testing Flat Surfaces."

Other laser applications include eye surgery, controlled fusion research, three dimensional photography, laser weapons, light shows, cancer research and accurate placement of the ball in football games. New applications are being developed continually.

LASER SAFETY PRECAUTIONS

Different lasers require different safety precautions. The following precautions must be observed in the operation of the low-power, helium-neon laser used in the laboratory portion of this module.

- Do not look directly into the laser beam. The lens of the eye will focus the laser beam to a small spot on the retina. Serious, permanent eye damage can result.
- Do not look at relfections of the beam from reflective surfaces. Mirrors, watch crystals, polished metal surfaces or other highly reflective surfaces reflect laser light with little decrease in the intensity of the beam. These reflections are as dangerous as the original beam.
- Take care when moving the laser or when moving objects into the laser beam. Direct and orient all beams and reflections to minimize the possibilities of accidental eye exposure.
- Beware of high voltages when operating the laser with case or enclosure opened. Laser power supplies contain high voltages. Electrical shocks account for more laser-related injuries than any other source.
- Operate the laser in a controlled area only. Be sure that everyone present is familiar with laser safety precautions.
- Do not track vehicles or aircraft with the laser beam. Such action could result in injury or property damage, and is forbidden by Federal law.
- Do not leave a laser unattended when it is operating or is in an operable condition. Always turn off the power switch and unplug the power cord. Store lasers where unqualified persons do not have access to them.

SUMMARY

Lasers produce light radiation concentrated into beams having the same wavelength and phase. Beams are emitted when an excitation mechanism (d.c. power supply or light source) provides energy to the atoms of an active medium (gas, solid or liquid), causing photons to be reflected from mirrors and finally as a beam through one of them (an output coupler). Beams have either a constant or a pulsed output. Laser operators must observe strict safety precautions to avoid injury.

The laser is one of the more important inventions of the twentieth century. New and vital laser applications are being developed constantly.

OPERATION OF A LOW-POWER, HELIUM-NEON LASER

MATERIALS

Low-power, helium-neon laser, 2 mW or less.
Shutter.
Beam block (block of wood painted with flat black paint).
Allen wrench or screwdriver to remove laser cover.

PROCEDURE

1. Begin with laser power switch in off position, power cord unplugged and shutter closed.
2. Place beam block to intercept laser beam about 30 cm from laser output aperture (Figure 8).
3. Plug in laser power cord.
4. Turn on laser power switch; wait ten seconds.
5. Open shutter.

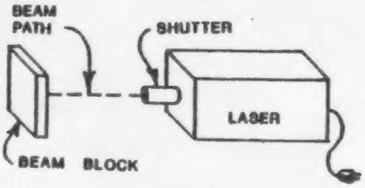


FIG. 8

6. Observe laser beam. This can be done by lightly dusting chalk dust or blowing smoke into path of beam. (Check with instructor.)
7. Move beam block along beam path to a distance of about 2 m from laser. Observe divergence of beam.
8. Turn off power switch; close shutter; unplug laser.
9. Use allen wrench or screwdriver provided to remove screws from laser cover or end plate. Remove cover or slide laser from housing (depending on model).
10. Examine laser tube; sketch in Data Table.
11. Carefully reassemble laser. Test assembled laser by operating according to instructions above. Observe all safety precautions.
12. How is a laser beam produced by this gas laser? (Refer to

the Discussion and to Figure 6.)

DATA TABLE
Sketch laser tube. Label parts.

SELF CHECK

1. Match each of the following properties of laser light with the characteristic it describes:

   (1) Monochromaticity.
   (2) Directionality.
   (3) Coherence.

   a. All light waves are in phase.
   b. Light leaves the laser in a narrow cone and spreads very slowly.
   c. Laser light contains very nearly only one wavelgnth.

2. Draw and label a diagram representing the stimulated emission process.

3. Name each of the following elements of a laser:

   a. A source of energy to excite atoms to the proper energy level for stimulated emission to occur.
   b. A collection of atoms that can produce light by stimulated emission.
   c. A partially transparent mirror that allows part of the laser light to leave the laser.
   d. A pair of mirrors to reflect laser light to continue the stimulated emission process.

4. List several important applications of lasers.

5. List all safety precautions to be observed in the operation of a low-power, helium-neon laser.

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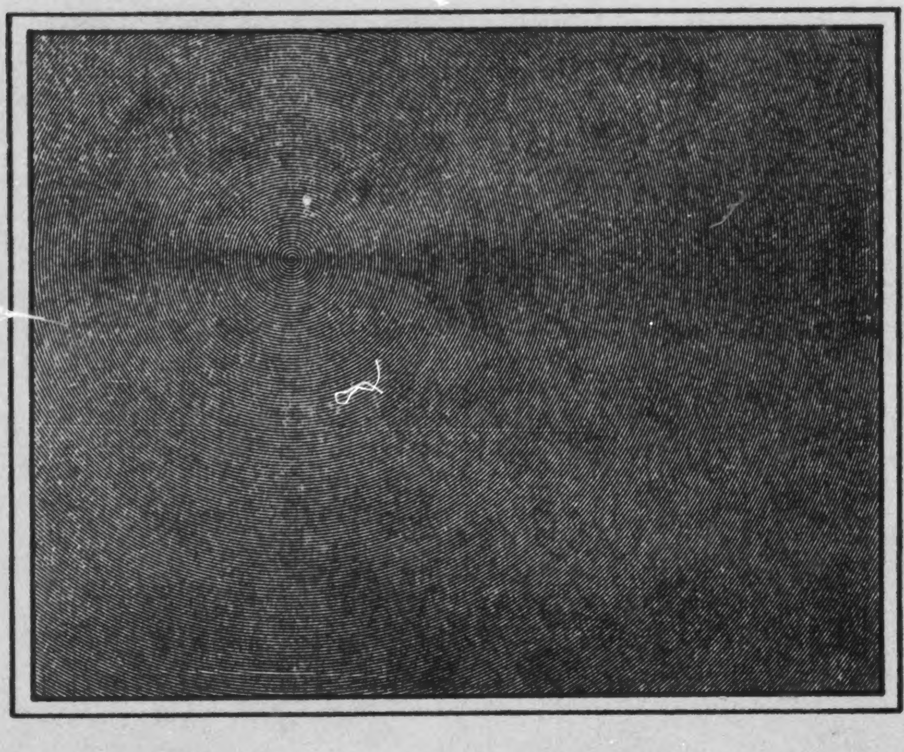
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 5
STROBOSCOPES
LIGHT PULSES



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Many applications of light radiation require that it be delivered in the form of short pulses. Photographic flashtubes, automobile timing lights and lasers produce bursts of radiant energy. This module discusses the stroboscope as a source of optical pulses. Both design features and applications of the stroboscope will be presented. In the laboratory, the student will use a stroboscope to measure the rotational rate of a fan and to observe water drop formation. He will also utilize an automobile timing light (strobe-light) to check the timing of an automobile engine.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Explain how a stroboscope may be used to "freeze" repetitive motion or greatly reduce its apparent rate for observation.
- Diagram a simple strobscope, and state the purpose of each of the major parts.
- Explain how an automobile engine timing light functions.
- Given the appropriate equipment, measure the rotational rate of an electric fan with a stroboscope; and connect a timing light to an automobile engine and observe the timing mark.

DISCUSSION

The stroboscopic effect is based upon the human sense of vision. Sensors of the eye respond to short optical pulses, but the information is processed rather slowly. The human visual system cannot separate two optical pulses which reach the eye in a time interval of less than about one tenth of a second. A succession of optical pulses arriving at the eye at a rate of over ten per second is seen as an unbroken sequence, and any periods of darkness between these pulses cannot be detected by the observer. Television and motion pictures are two common applications of this principle. Both produce stationary images at a rate exceeding the resolving ability of human vision. Thus, images appear to move with an unbroken, continuous motion.

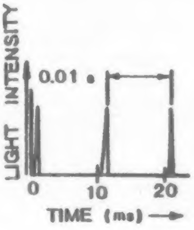


FIG. 1

The stroboscope is a device that produces short optical pulses at a predetermined rate. A typical stroboscope can be adjusted to emit from 1 to 100 pulses per second, with a pulse duration of about 5 microseconds. The time-varying output of a stroboscope at 100 pulses per second is shown in Figure 1. At this rate, the period of darkness between two adjacent pulses lasts two thousand times as long as one of the optical pulses.

Figure 2 shows how stroboscopic light can be used to "freeze" repetitive motion for observations and measurements. The object to be studied is a rotating disk upon which an arrow is painted. The stroboscope is set to produce one output pulse for each revolution of the disk. Figure 2a shows the disk illuminated by a brief pulse of light. Figures 2b and 2c show the disk continuing its rotation with no illumination. After one revolution is completed (Figure 2d), another pulse of light from the stroboscope illuminates the disk in its original position. This process continues, with an optical pulse being generated at the same point during each rotation of the disk. To a human observer, the disk appears to be stationary.

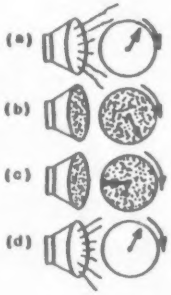


FIG. 2

As the pulse repetition rate and the rotation rate become lower, the time interval between pulses or rotation becomes greater. If the pulse repetition rate of the stroboscope is slightly less than the rotation rate of the disk (Figure 3), the disk will rotate slightly more than one complete revolution between light pulses. To an observer, the disk will appear to rotate in its actual direction of rotation at a greatly reduced rate. If the pulse repetition rate of the stroboscope is slightly greater than the rotation rate of the disk (Figure 4), the disk will be illuminated before it completes its revolution, and it will appear to rotate slowly in the direction opposite to its actual direction of rotation. This process can be used to make a detailed analysis of the repetitive motion of high-speed machinery during actual operating conditions.

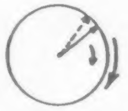


FIG. 3

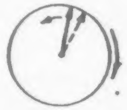


FIG. 4

A stroboscope may be used also as a light source for photography, to make a permanent record of motion. Figure 5 shows a photographic record of a falling body made with stroboscopic light.

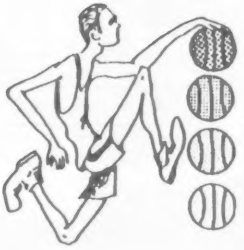


FIG. 5

The same techique is used to examine high-velocity motion, such as bullets in flight.

Figure 6 shows a simplified diagram of a stroboscope. Light is produced by a current pulse through a flashlamp filled with neon or xenon. The internal resistance of this lamp provides the resistance of the RLC circuit. The d.c. power supply charges the capacitor to several hundred volts. This is not sufficient voltage to cause the lamp to conduct, but it does provide the short current pulse when the gas is ionized. Ionization is accomplished with a high-voltage pulse (several kilovolts) from a pulse circuit. This pulse is delivered to a trigger wire on the outside of the flashlamp. Timing of this pulse may be controlled by either an internal timer or some external trigger signal.

Figure 7 is a simplified diagram of an automobile-engine timing light, a common application of stroboscopic light. As in the more complex stroboscope, the d.c. power supply charges a capacitor to provide operating current for the lamp. The inductor is usually omitted to reduce circuit cost and size. Triggering is accomplished by connecting the high-voltage pulse from the number one spark plug directly to the trigger wire of the lamp. Thus, the lamp produces a pulse of light each time the spark plug fires, allowing precise timing for the firing of the plug.

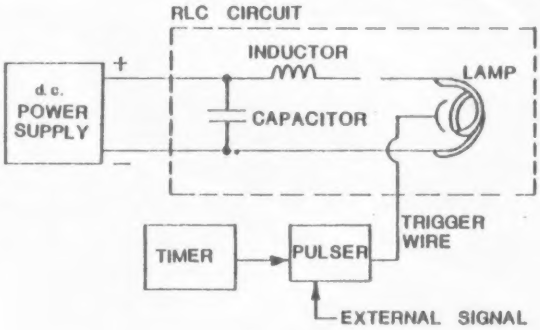


FIG. 6

SUMMARY

The stroboscope delivers light in short pulses useful in "freezing" action and in measuring the rate of action. Light is produced by a current pulse through a flashlamp filled with neon or xenon. A typical stroboscope is capable of emitting from 1 to 100 pulses per second, with a pulse duration of approximately 5 microseconds.

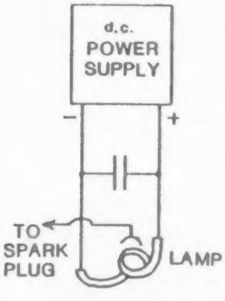


FIG. 7

MEASURING ROTATIONAL RATE OF FAN

MATERIALS

Stroboscope.
Electric fan.
Tape.

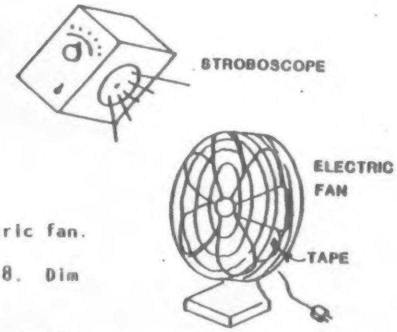


FIG. 8

PROCEDURE

1. Place a strip of tape on one blade of electric fan.
2. Set stroboscope and fan as shown in Figure 8. Dim room lights.
3. Turn on fan and stroboscope. Adjust pulse repetition rate of stroboscope until fan blades appear to stand still. If tape strip appears on more than one blade, decrease pulse repetition rate until tape appears on one blade only (Figure 9). Read rotational rate (from stroboscope meter or from frequency-selection dial, depending upon stroboscope used); record in Data Table.
4. Set pulse repetition rate of stroboscope to twice that recorded above. Make fine adjustments to "stop" fan blades.
5. Continue above process, doubling pulse repetition rate each time. Explain appearances of the fan blade like the one shown in Figure 10. Record multiple frequences which just "stop" the blades.
6. True rotational rate of fan is the greatest pulse repetition rate for which tape strip appears on one blade only. Record true rotational rate in Data Table.
7. How could these laboratory principles be used to measure the rotational rate of a rotating piece of machinery?

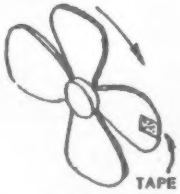


FIG. 9

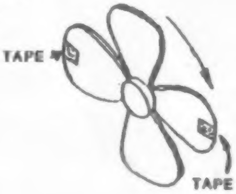


FIG. 10

OBSERVING DROP FORMATION

MATERIALS

Stroboscope.
Source of running water (tap).

PROCEDURE

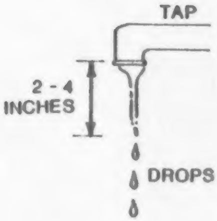


FIG. 11

1. Turn on water; obtain stream of drops (Figure 11). Unbroken stream of water should extend 2 to 4 inches from tap as shown.
2. Dim room lights; illuminate water stream with stroboscope.
3. Adjust pulse repetition rate of stroboscope until water drops appear to be stationary. Slight variations in frequency will cause drops to appear to either fall or rise slowly.
4. Observe drop formation.
5. How could photography with a strobe light "stop" the action of the falling drops?

OPERATING AUTOMOBILE ENGINE TIMING LIGHT

MATERIALS

Automobile.
Timing Light.

PROCEDURE

1. With automobile engine stopped, connect timing light as follows:

   Red wire to positive terminal of battery.
   Black wire to negative terminal of battery.
   Third wire to number one spark plug.

2. Be sure all wires are clear of moving parts; start engine.

3. Point timing light at timing marks at front of crankshaft (Figure 12). Press switch of timing light; observe alignment of moving mark (on crankshaft pulley or harmonic damper) with fixed marks.

4. How does this laboratory procedure demonstrate the principles in the Discussion of rotating disks and Figures 2, 3 and 4?

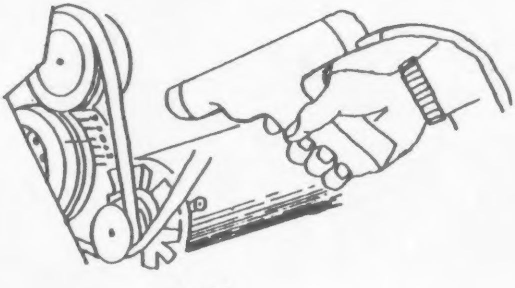


FIG. 12

DATA TABLE

Rotational Rate of Fan

First reading = ______ rpm
Second reading = ______ rpm
Third reading = ______ rpm
Fourth reading = ______ rpm

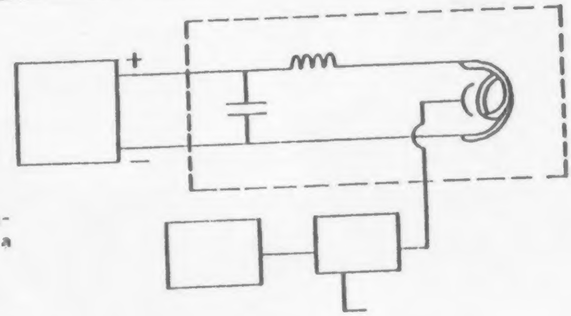
True rotational rate of fan = ______ rpm

SELF CHECK

1. Indicate with a series of sketches showing a rotating body the timing of stroboscopic pulses of light to "freeze" the motion of the object.

2. Explain how a stroboscope may be used to observe high-speed repetitive motion at a greatly reduced rate.

3. Label the diagram on the right, showing the parts of



a stroboscope.

4. Draw and label a diagram, showing the parts of an automobile engine timing light.

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Wanninger, Albert. Using Electronic Testers for Automotive Tune-up. Blue Ridge Summit, PA: Tab Books, 1972.

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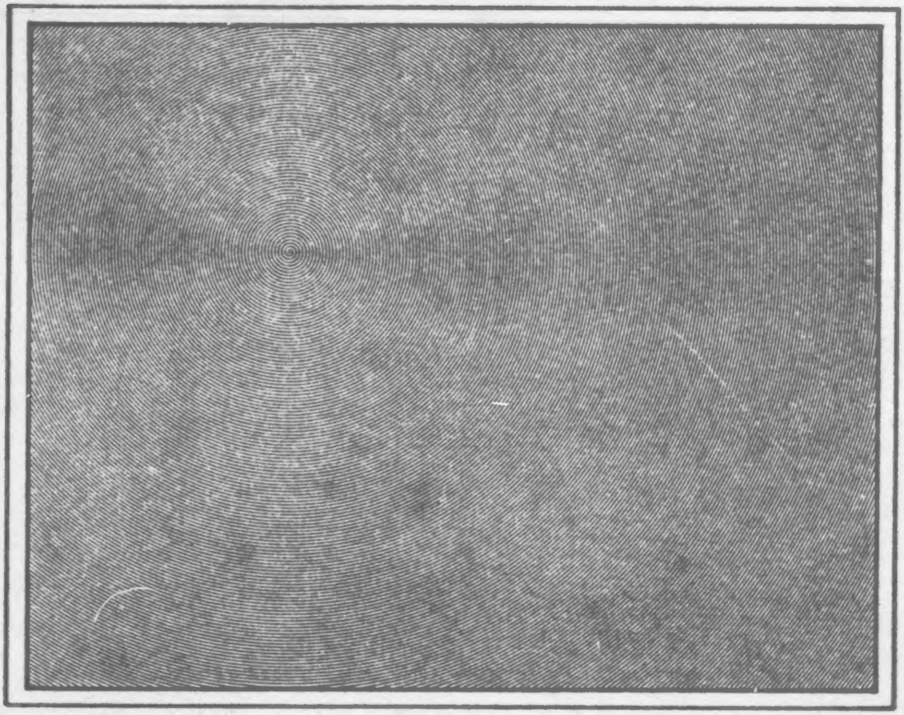
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 6
OPTICAL FILTERS
ABSORPTION OF LIGHT



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Often the intensity or wavelength distribution of light produced by a light source does not meet the requirements of the application. In such cases, optical filters may be employed to absorb the unwanted electromagnetic radiation (light) while allowing the desired EM radiation to pass through. This module will discuss the absorption of light by matter and will present a description of several common types of optical filters. The exponential law of absorption will be explained and verified in the laboratory.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Modules 1S3, "Logarithms," 13L2, "The Optical Spectrum," and 13L4, "Lasers."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Explain in a short paragraph how light is absorbed; include what happens to the energy after it is absorbed by the material.
- Explain with a diagram and in a short paragraph the exponential law of absorption.
- Given two of the following quantities, calculate the third;

  Absorption coefficient of a filter at a specified wavelength.
  Thickness of filter.
  Transmission of filter at the specified wavelength.
- Describe in two or three sentences for each of the following filters how the transmission varies with changes in the wavelength of light:

  Neutral density.
  Cut-off.
  Band-pass.

Color.

- Given the optical density of a filter, calculate its transmission.
- Measure the transmission of an optical filter material as a function of thickness at a single wavelength and calculate its absorption coefficient given the appropriate equipment.

DISCUSSION

ABSORPTION OF LIGHT

Figure 1 shows a beam of light traveling through an optical filter. I_o is intensity of the light incident upon the material and I is the intensity of the light emerging from the material. Equation 1 gives the transmission of the filter.

$$T = \frac{I}{I_o} \qquad (1)$$

where

T = transmission.
I_o = incident intensity.
I = transmitted intensity.

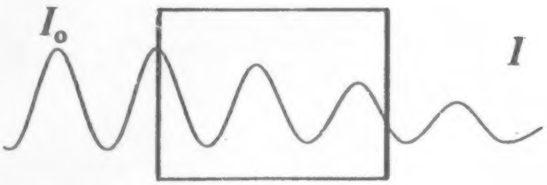


FIG. 1

In some cases most of the light is transmitted ($T = 0.999$) and in others there is no transmission at all ($T = 0$), but the transmission is always less than one. The question that must be answered is: what happened to that portion of light energy that was not transmitted?

Figure 2 contains a simplified energy level diagram of an atom. The horizontal lines represent definite amounts of energy that the atom may contain. An upward arrow indicates an energy gain by the atom and a downward arrow indicates an energy loss. The atom is initially in the lowest energy state E_1, called the atomic ground state. The incident photon has an energy equal to the energy difference between energy levels E_1 and E_3. When the photon strikes the atom, it is absorbed, ceases to exist, and its energy appears as increased energy in the atom.

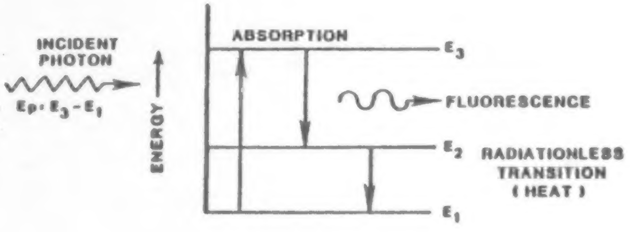


FIG. 2

Most atoms remain in an excited energy state for only a short time (average of 10^{-8} s).

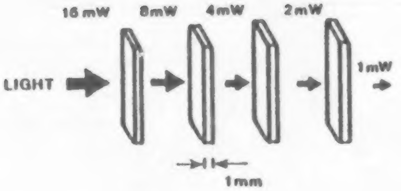


FIG. 3

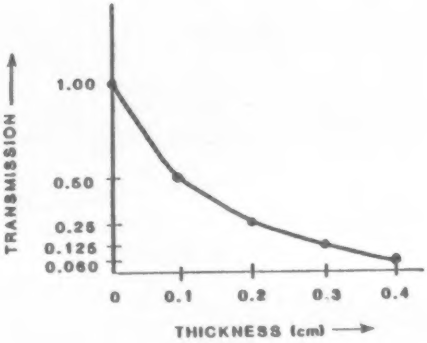


FIG. 4

They may release their excess energy by emitting it in the form of photons. This process is called fluorescence and is the mechanism used to produce visible light in fluorescent bulbs. Another energy release process is the radiationless transition shown in Figure 2. The electronic energy of the atom is converted to kinetic energy in liquids and gases or vibrational energy in solids. This appears as heat and causes a temperature rise in the material.

EXPONENTIAL LAW OF ABSORPTION

It is obvious that increasing the thickness of an absorbing material will decrease the intensity of the transmitted light. Figure 3 shows light traveling through four pieces of identical filter material (each 1 mm in thickness). Each piece absorbs half of the light incident upon it. Figure 4 shows a graph of transmission versus thickness for this material. The transmission of an optical filter may be calculated using the exponential law of absorption given in Equation 2.

$$T = e^{-kx} \qquad (2)$$

where

T = transmission.
k = absorption coefficient in cm^{-1}.
x = thickness in cm.
e = Naperian base (2.718).

In this equation the thickness x is always expressed in cm and the absorption coefficient k is in cm^{-1}. Example A illustrates how this equation is used in solving a typical problem.

EXAMPLE A: TRANSMISSION CALCULATION

Given: Absorption coefficient of the material in Figure 3 is $6.93\ \text{cm}^{-1}$.

Find: Transmission through a 2 mm thickness of this material.

Solution:

$$T = e^{-kx}$$

$$k = 6.93\ \text{cm}^{-1}$$

$$x = 2\ \text{mm} = 0.2\ \text{cm}$$

$$\therefore\ T = e^{-(6.93\ \text{cm}^{-1})(0.2\ \text{cm})}$$

$$= e^{-1.386}$$

$$T = 0.25$$

The absorption coefficient for a material may be calculated from Equation 3 if the transmission and thickness are known.

$$k = \frac{1}{x}\ \ln\left(\frac{1}{T}\right) \qquad (3)$$

Example B shows how Equation 3 and Equation 1 are used in solving a problem.

EXAMPLE B: CALCULATING ABSORPTION COEFFICIENT

Given: A 10-mW laser beam strikes a piece of filter material 1.2 cm thick. 0.42 mW is transmitted.

Find: Absorption coefficient of material.

Solution:

$$T = \frac{I}{I_o}$$

$$= \frac{0.42\ \text{mW}}{10\ \text{mW}}$$

$$T = 0.042.$$

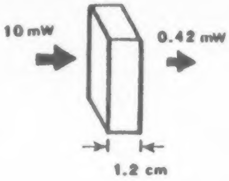
$$k = \frac{1}{x}\ \ln\left(\frac{1}{T}\right)$$

$$= \frac{1}{1.2\ \text{cm}}\ \ln\left(\frac{1}{0.042}\right)$$

$$= \frac{1}{1.2\ \text{cm}}\ \ln(23.8)$$

$$= \frac{3.17}{1.2\ \text{cm}}$$

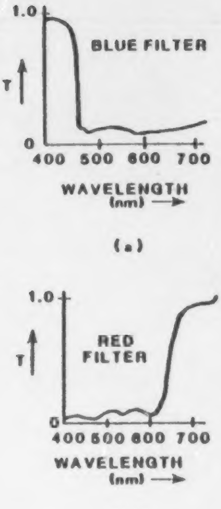
$$k = 2.64\ \text{cm}^{-1}$$



OPTICAL FILTERS

The absorption coefficient of any material (and thus its transmission) is a function of the wavelength of light striking the filter. Thus far, discussion in this module has dealt with thickness variations of absorbing materials at a single wavelength. This section assumes a fixed thickness and presents transmission variations as the wavelength of light changes.

Figure 5 shows transmission of two optical filters as functions of wavelength. The blue filter in Figure 5a allows most of the blue light to pass but absorbs other colors of the visible spectrum. The red filter (Figure 5b) allows only red light to pass through. These filters have a sharp division between high and low transmission regions and are called cut-off filters. They are used to eliminate unwanted wavelengths in many optical systems.



(a)

(b)

FIG. 5

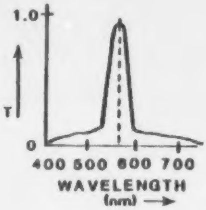


FIG. 6

Figure 6 is the transmission curve of a band-pass filter. This type of filter passes a narrow band of wavelengths but blocks all light outside this band. Darkroom safe lights use band-pass filters that pass only those wavelengths to which the film is not sensitive.

Transmission of a neutral density filter is shown in Figure 7. This filter is designed to have the same transmission for all wavelengths over a broad range of the spectrum. Neutral density filters can be made for any region of the optical spectrum. The gray lenses of most sunglasses are neutral density filters for visible light.

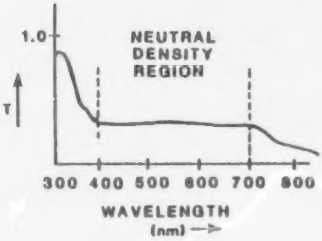


FIG. 7

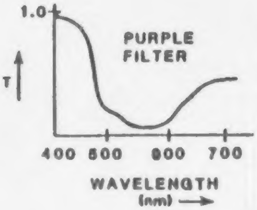


FIG. 8

Colored filters of glass or plastic are often used in lighting systems and decorative applications such as colored windows. Figure 8 is the transmission curve of a purple filter. The purple color is produced by a combination of blue and red light. Color filters are available in a wide variety of colors.

A term often used to describe the transmission of neutral density filters, laser safety goggles and other low-transmission filters is optical density. If the optical density of a filter is known, its transmission may be calculated from Equation 4.

$$T = 10^{-OD} \qquad (4)$$

when T = transmission.
OD = optical density.

Example C shows how this equation is used in solving a problem.

EXAMPLE C: CALCULATION OF TRANSMISSION FROM OPTICAL DENSITY

Given: The optical densities of two filters are:
a. 3.0.
b. 0.3.

Find: Transmission of each filter.

Solution:
a. $T = 10^{-3}$
$T = 0.001$
b. $T = 10^{-0.3}$
$T = 0.50$

SUMMARY

Whenever light passes through any material some of the light is absorbed. The fraction of the light that is transmitted through a material depends on the absorption coefficient of the material at the light wavelength and the thickness of the filter. Increasing the thickness of optical material reduces the transmission according to the Exponential Law of Absorption. Optical filters are constructed by selecting materials that have a low absorption coefficient for the wavelengths to be transmitted and a high absorption coefficient for the wavelengths that are to be blocked.

LABORATORY

MATERIALS

Low-power helium-neon laser, 2 mW or less.
Optical power meter.
Optical bench.
Filter holder.
Two carriages.
Lab jack.
Metric micrometer.
Plastic color filters of uniform thickness cut to fit filter holder (5 pieces of light red; 5 pieces of light green).

PROCEDURES

1. Review laser safety precautions.

2. Set up equipment as shown in Figure 9.

3. Observing all safety precautions, turn on laser; align beam to pass through center of empty filter holder and strike detector surface of power meter. Allow laser to operate for 15 minutes before taking data. This warm-up time will minimize output fluctuations.

4. Measure and record output power of laser with no filters in beam. If periodic variations occur in laser output, take power readings at maximum power attained. Use this procedure throughout the measurements.

5. Place one piece of red filter in filter holder. Measure and record transmitted power.

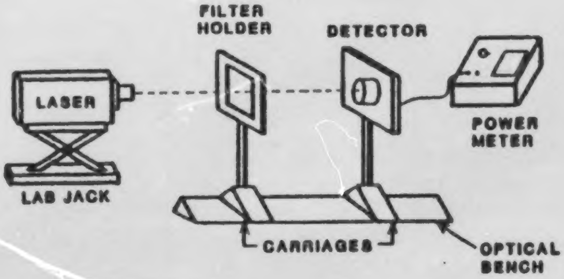


FIG. 9

6. Place additional red filters in holder,

measuring power as each filter is added.

7. Remove red filters; repeat with green filters.

8. Turn off laser.

9. Use micrometer to measure thickness of one piece of filter of each color. Record thickness in data table.

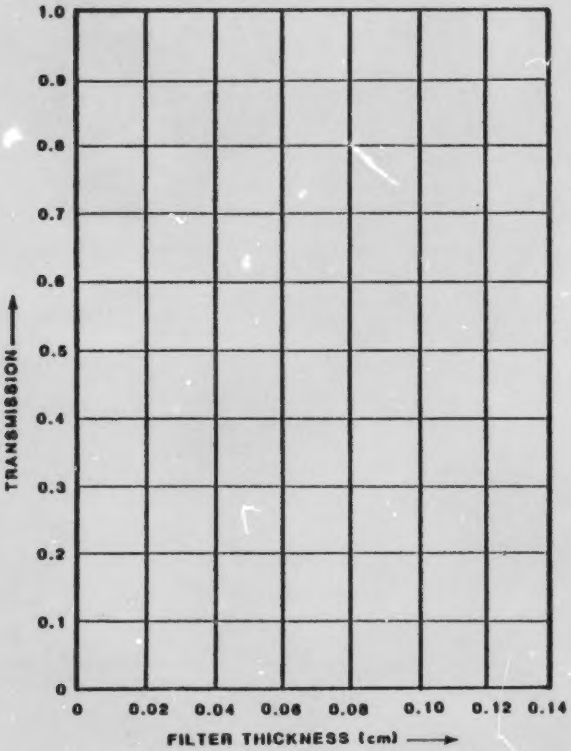
10. Calculate transmission for each measurement of both red and green filters by dividing transmitted power by power recorded for laser with no filters.

11. Calculate total filter thickness in each case by multiplying thickness of one filter by number of filters used.

12. Using Equation 3, thickness of five pieces of filter material and transmission of the five filters, calculate absorption coefficient of red and green filters for helium-neon laser light.

13. Draw curves showing transmission versus thickness for both filter materials on graph paper provided; label each curve and compare to Figure 4.

DATA TABLE							
Red Filter Filter thickness = __________ cm.				Green Filter Filter thickness = __________ cm.			
Total Filter Thickness		Transmitted Power (mW)	Transmission	Total Filter Thickness		Transmitted Power (mW)	Transmission
No. of Pieces	(cm)			No. of Pieces	(cm)		
0				0			
1				1			
2				2			
3				3			
4				4			
5				5			



Absorption coefficient. Red: k = ______ cm^{-1}

Green: k = ______ cm^{-1}

SELF CHECK

1. Draw and label a simple energy level diagram showing absorption of light by an atom. Include possible transitions that may remove the energy from the atom.

2. Draw a curve showing transmission of an optical filter as a function of thickness at one wavelength.

3. A filter 0.5 cm thick has an absorption coefficient of 6.3 cm^{-1} at a wavelength of 450 nm. Calculate its transmission at that wavelength.

4. A piece of glass 1.2 cm thick has a transmission of 0.82 at 633 nm. What is its absorption coefficient at that wavelength?

5. Draw a curve showing transmission of each of the following as a function of wavelength:

   Color filter.
   Neutral density filter.
   Cut-off filter.
   Band-pass filter.

6. The optical density of a filter is 2.0. What is its transmission?

REFERENCES

Technical Education Research Center - Southwest, ed. "Lasing Action." Module 1-6, Laser/Electro-Optics Series. Waco, TX: TERC-SW, 1976.

Technical Education Research Center - Southwest, ed. "Filters and Beamsplitters." Module 6-6, Laser/Electro-Optics Series. Waco, TX: TERC-SW, 1976.

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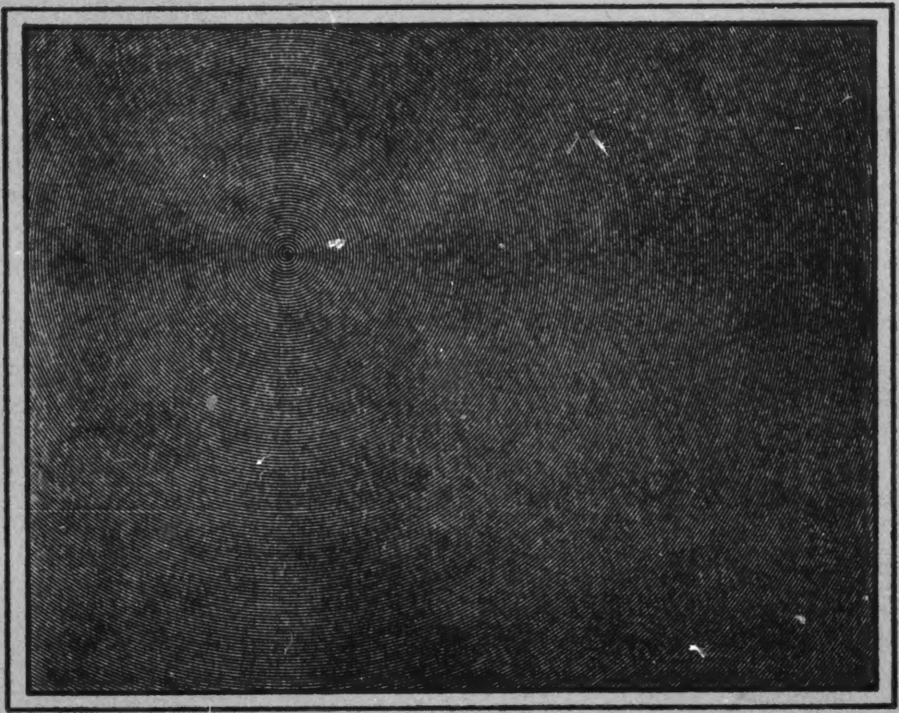
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 7

SPECULAR AND DIFFUSE REFLECTION OF LIGHT



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Most applications of light require that the direction of travel of the light waves be changed between the light source and some detector. The most common way to accomplish this is by reflection. The human eye itself is a complex detector system for analyzing light reflected from objects. This module presents the law of reflection of electromagnetic radiation and applications of that law to a variety of reflecting surfaces. Specular and diffuse reflectors and partial and total reflection will be discussed. Students will measure light reflected from specular and diffuse reflectors in the laboratory.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13L4, "Lasers."

OBJECTIVES

To complete this module, the student should be able to:

- State the law of reflection and illustrate with a simple diagram.
- Define and illustrate specular reflection and diffuse reflection.
- Give three examples each of specular and diffuse reflectors.
- List the four processes that account for all light energy striking a surface.
- Explain in two or three sentences the purpose and operation of a beamsplitter.
- Given appropriate equipment, measure the distribution of laser light reflected from specular and diffuse reflecting surfaces.

DISCUSSION

The reflection of light may be studied by considering light to be composed of rays that travel in straight lines except for reflection or refraction at surfaces. Wave properties of light need not be considered when discussing reflection of light from most surfaces.

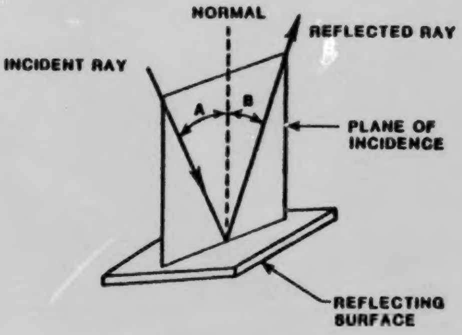
LAW OF REFLECTION

Figure 1 shows a light ray reflected from a plane surface. The normal line is a line perpendicular to the optical surface at the point of reflection. All angles are measured from this line. The incident ray, reflected ray and normal all lie in a plane called the plane of incidence. The law of reflection is given by Equation 1.

Law of reflection:

angle of reflection = angle of incidence,

or $\angle A = \angle B$ (1)



A = ANGLE OF INCIDENCE
B = ANGLE OF REFLECTION

FIG. 1

SPECULAR AND DIFFUSE REFLECTORS

A specular reflector is a smooth reflecting surface such as an ordinary mirror that reflects light according to the law of reflection and maintains internal order of the light beam. Figure 2 shows a light beam reflected from a plane specular reflector. In Figure 3 a similar beam is reflected from a curved specular reflector. In this case different parts of the beam are reflected at different angles but the internal order of the light rays is maintained after reflection.

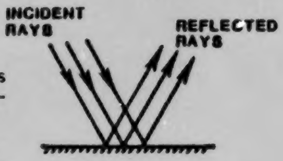


FIG. 2

A diffuse reflector is a rough reflecting surface, such as this sheet of paper, that reflects light randomly in all directions and does not maintain internal order in a light beam. Figure 4 shows reflection of light from such a surface. Each flat surface element of a diffuse reflector acts as a tiny mirror, and reflections from each element obey the law of reflection. Because of the random orientation of the flat surface elements, diffuse reflecting surfaces reflect light in all directions. Figure 5 shows the radiation pattern from a diffuse reflector when it is struck by a beam of light.

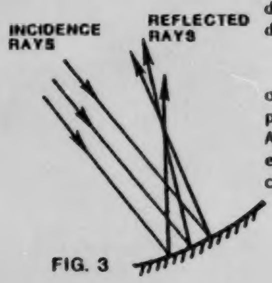

INCIDENCE RAYS
REFLECTED RAYS

FIG. 3

Many surfaces display a combination of the characteristics of specular and diffuse reflectors. Figure 6 shows the typical pattern of light reflected from a glossy painted surface. Although some diffuse reflection takes place, most of the light energy is found in specular reflection and this surface is classed as a specular reflector.

PARTIAL AND TOTAL REFLECTORS

When light strikes a surface, some of the light energy is always reflected. But no surface can reflect all of the light that strikes it. Figure 7 shows light striking an optical surface. Part of the light is reflected (1), part is transmitted (2), a third portion is scattered due to diffuse reflections from surface imperfections (3), and a fourth part is absorbed by the optical material. The total energy of the incident light beam must be accounted for in these four processes as given in Equation 2.

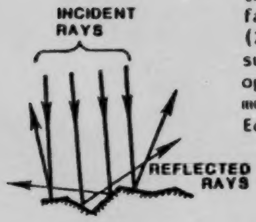

INCIDENT RAYS
REFLECTED RAYS

FIG. 4

Incident energy = scattered energy + transmitted energy + absorbed energy + reflected energy, or

$$E_I = E_S + E_T + E_A + E_R$$

or

$$E_I = S + T + A + R. \qquad (2)$$

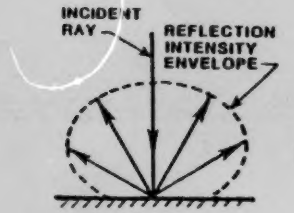

INCIDENT RAY
REFLECTION INTENSITY ENVELOPE

FIG. 5

Example A shows the use of this equation in solving a problem.

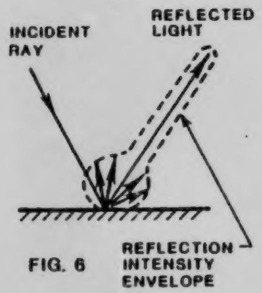

INCIDENT RAY
REFLECTED LIGHT
REFLECTION INTENSITY ENVELOPE

FIG. 6

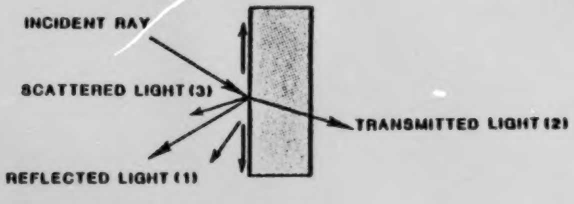

INCIDENT RAY
SCATTERED LIGHT (3)
TRANSMITTED LIGHT (2)
REFLECTED LIGHT (1)

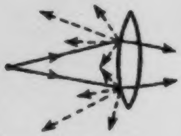
FIG. 7

EXAMPLE A: REFLECTION LOSS OF A LENS

Given: A lens has a transmission of 92%. The total of absorption and scattering is 0.5%.

Find: Total reflection loss.

Solution:



$$E_I = S + T + A + R$$

$$100\% = 0.5\% + 92\% + R$$

$$R = 100\% - 92.5\%$$

$$R = 7.5\%$$

Some light energy always goes into each of the four processes. Scattered light is undesirable in most optical systems and can be reduced to near zero intensity (0.01%) by polishing the optical surfaces and keeping them clean. Clean glass surfaces scatter so little light that scattering usually can be ignored. Absorption also reduces the intensity of the transmitted beam, removing light energy from the incident beam. Ordinary bathroom mirrors absorb 10 to 15% of the light that strikes them. In many highly transmitting optical components, absorption is reduced to almost zero. Ordinary glass windows absorb very little light. In windows maximum transmission is desirable while in other applications no light is transmitted.

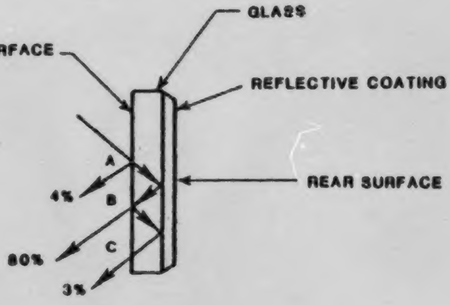


FIG. 8

A portion of the light is always reflected. Ordinary glass reflects about 4% of the light that strikes it at each of its surfaces. Figure 8 shows light striking a rear surface mirror. About 4% of the light is reflected by the glass surface at point A. When the main reflected beam leaves the glass at point B, about 4% of it

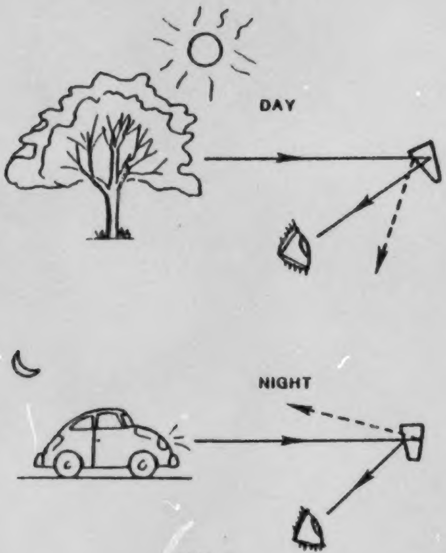


FIG. 9

is reflected back into the glass. Most of this light (about 3% of original beam) passes out of the glass as shown at point C. The two weaker reflected rays often form ghost images in mirrors. This can be eliminated by applying the reflective coating to the front surface of the mirror, but this also exposes the reflective coating to possible damage.

Figure 9 shows how partial reflection is employed in rear vision mirrors for automobiles. Such mirrors are actually optical wedges with the rear surface silvered. During the day the more intense reflection from the silver coating is viewed. At night the weaker reflection from the front surface is used to reduce light intensities from the headlights of trailing cars.

Coatings are often applied to optical surfaces to change their reflectivity. Highly reflective laser mirrors may reflect as much as 99.95% of the laser light that strikes them. Camera and telescope lenses often have antireflection coatings to reduce reflections to less than 1%.

BEAMSPLITTERS

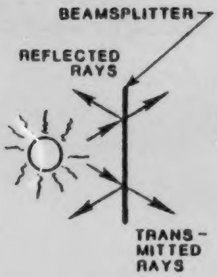


FIG. 10

In many applications it is desirable to reflect only a portion of the light striking a surface while allowing the remainder to pass through. This is accomplished with the partially reflective optical surface of a beamsplitter shown in Figure 10. The ratio of transmitted to reflected light may be set at any desired value. Beamsplitters are used in many optical instruments (including interferometers and range finders) but also have several more common applications. The partially reflective windows of many office buildings are in actuality applications of beamsplitters.

Figure 11 shows an electronic game using a beamsplitter. The gun is a light source that sends a beam toward a target. Part of the beam reaches the target in the back of the cabinet, but the score is recorded when the reflected beam strikes a detector in the base of the cabinet. The operator sees only the target and is unaware of the beamsplitter or detector.

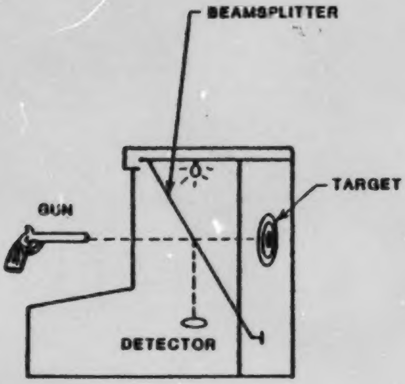


FIG. 11

SUMMARY

Whenever light strikes a surface it may be reflected, scattered, absorbed or transmitted. In most common optical components absorption and scattering account for only a small fraction of the total light energy. Thus, most of the light is reflected from the surface or transmitted through the optical component.

A diffuse reflector is a rough surface that reflects incident light in all directions. A specular reflector is a smooth mirror-like surface that reflects light rays according to the law of reflection:

angle of incidence = angle of reflection

Some light is always reflected from any optical surface. Mirrors reflect most of the light while beamsplitters reflect a portion and allow the remainder to be transmitted.

SPECULAR AND DIFFUSE REFLECTIONS OF A LASER BEAM

MATERIALS

Low-power helium-neon laser (2 mW or less).
Optical power meter (Metrologic #60-530 or equivalent).
Protractor.
Large compass (7-inch minimum), or string and tack.
Ruler.
Plane front surface mirror (Edmund #40.040 or equivalent).
White index card glued to block of wood.
White enamel surface (flat metal painted with gloss enamel paint).
Sheet of paper 8 1/2 inches x 14 inches.

PROCEDURES

CAUTION: AVOID LOOKING INTO LASER BEAM, EITHER DIRECTLY OR WHEN BEAM IS REFLECTED OFF A SURFACE. THE BEAM CAN CAUSE EYE DAMAGE.

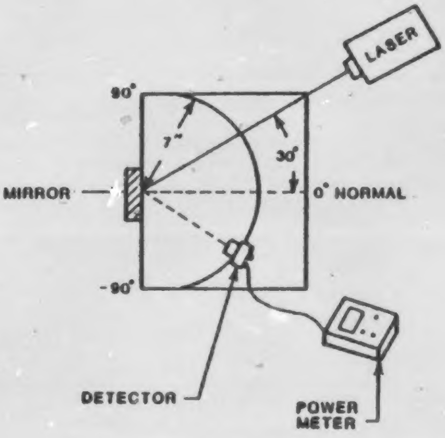


FIG. 12

1. Use compass to draw a semicircle with a radius of about 7 inches on sheet of paper as shown in Figure 12. From center of semicircle, draw radial lines every 10° to correspond to graph paper in graph section of data.

2. Arrange equipment as shown in Figure 12. Observe all laser safety precautions. Laser beam should be level and should strike mirror surface at center with angle of incidence of 30°.

3. Dim room lights.

4. With laser and mirror stationary move power meter detector; measure reflected optical power at 10° intervals along semi-

circle. Record power in data table. Be sure detector surface is always at same distance from point of reflection and perpendicular to reflected light. Some measurements will require most sensitive scales of power meter. Be careful not to drive needle past full scale.

5. Replace mirror with index card; repeat entire procedure for diffuse reflection from paper.

6. Replace index card with enamel surface; repeat. Record data in combination column in data table.

7. Plot data on graph paper provided in graph section. Plot power recorded along radial line at approximate angles. Radial distance on graph is therefore power in watts measured on the logarithmic scale of the power meter. Connect all data points with smooth curve.

8. Compare the resulting intensity patterns to those predicted in the discussion. (See Figures 5 and 6).

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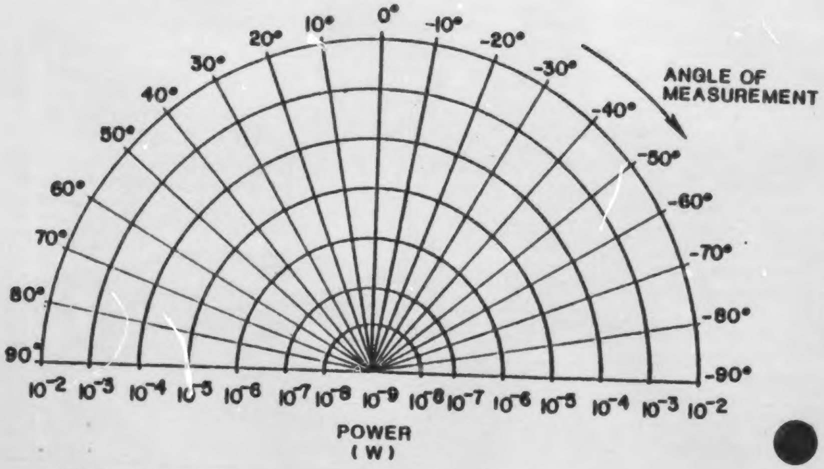
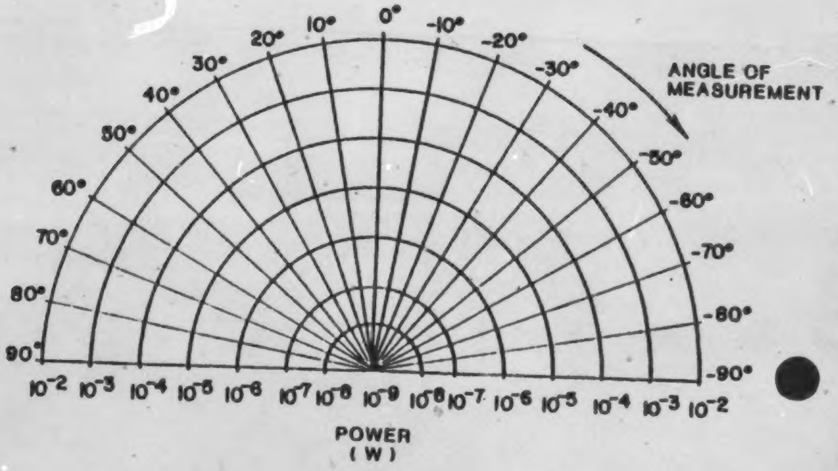
DATA TABLE			
Angle of Measurement (degrees)	Reflected Power Measured (W)		
	Specular	Diffuse	Combination
-90			
-80			
-70			
-60			
-50			
-40			
-30			
-20			
-10			
0			
10			
20			
30			
40			
50			
60			
70			
80			
90			

Specular Reflector



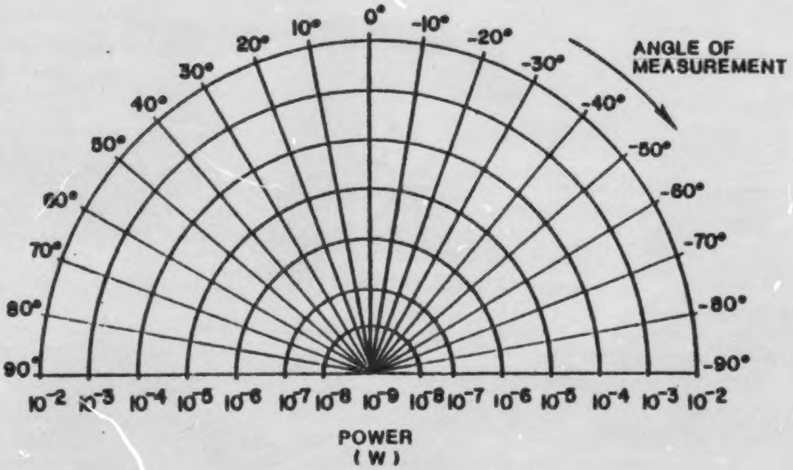
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
ANGLE OF MEASUREMENT
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
POWER (W)

Diffuse Reflector



0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
ANGLE OF MEASUREMENT
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
POWER (W)

Third Reflector (Combination)



SELF CHECK

1. Draw and label a diagram illustrating the law of reflection.

2. Draw and label diagrams showing light reflected from specular and diffuse reflecting surfaces.

3. Identify the following as specular or diffuse reflectors:

   Bathroom mirror.
   Sheet of paper.
   Ceiling tile.
   Watch crystal.
   Shiny linoleum tile.

4. Draw and label a diagram of light striking a beamsplitter at an incident angle of about 30°. Show both the transmitted and the reflected ray.

5. A beamsplitter reflects 49% of the light striking it and transmits 48% of the light. What happens to the other 3%?

6. Name the four processes that account for all light striking a surface.

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Jenkins, Francis A. and White, Harvey E. Fundamentals of Optics. New York: McGraw-Hill Book Co., 1957.

Technical Education Research Center - Southwest, ed. "Reflection and Refraction." Module 5-4, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

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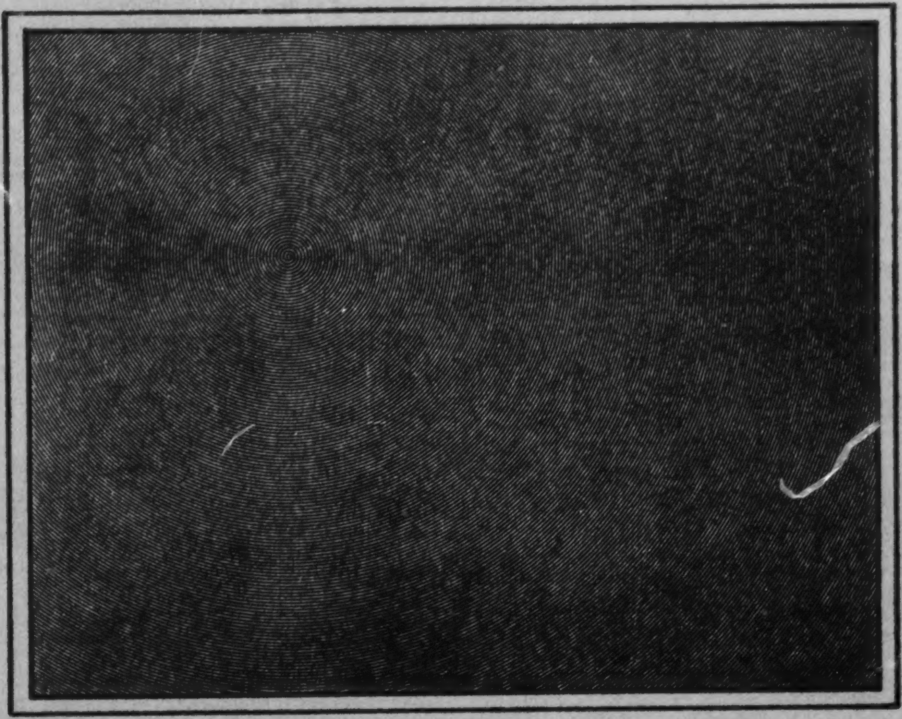
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 8

IMAGE FORMATION WITH MIRRORS



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Mirrors are devices that change the direction of travel of light rays by reflection. Mirror surfaces are usually plane, spherically convex or spherically concave. Such mirrors may be used to focus light to a small area, collimate light beams, form images, or simply change the direction of a beam of light. This module discusses reflections from plane and shperical surfaces, as well as the images formed by these reflections under different conditions. In the laboratory, the student will use a concave mirror to construct a solar furnace and to produce real and virtual images.

PREREQUISITES

Student should have completed Concept Moudle 13-0, "Radiation," and Application Module 13L7, "Specular and Diffuse Reflection of Light."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Real image.
  Virtual image.
  Focal point of a concave mirror.
  Focal point of a convex mirror.

- Draw and label ray diagrams that illustrate:

  Virtual image formed by a plane mirror.
  Virtual image formed by a convex mirror.
  Virtual image formed by a concave mirror.
  Real image formed by a concave mirror.

- Given two of the following quantities, calculate the third:

  Focal length of mirror.
  Object distance.
  Image distance.

- Given three of the following quantities, calculate the fourth:

  Object distance.
  Image distance.
  Object height.
  Image height.

- Given appropriate equipment, construct a solar furnace.

- Given the appropriate equipment, demonstrate formation of real and virtual images formed by a concave mirror.

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optical axis. (It is just the reverse of ray B, described in Figure 5.)

Figure 7 shows the formation of a real image by a concave mirror when the object is located between the focal point and the center of curvature.

Shown in Figure 8 is the formation of a virtual image by a convex mirror. As in a plane mirror, the image is the apparent origin of the reflected rays. This image is the only type produced by convex mirrors.

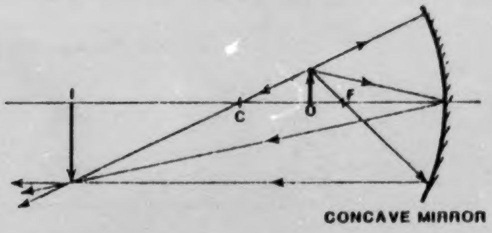

FIG. 7

IMAGE LOCATION AND SIZE

The location of an image formed by any mirror may be calculated by using Equation 1:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \qquad (1)$$

where
f = focal length.
p = object distance.
q = image distance.

In this equation, p is the distance from the object to the mirror surface along the optical axis, and q is the distance from the image to the mirror surface.

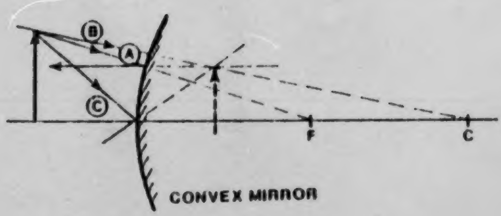

FIG. 8

Concave mirrors have a positive focal length and convex mirrors have a negative focal length. The image distance is positive for real images and negative for virtual images. Examples A and B show the use of Equation 1 for solving problems.

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Ray A is the light ray from the top of the object, through the center of curvature of the mirror, to the mirror surface. It will always be perpendicular to the mirror surface and is reflected back along itself.

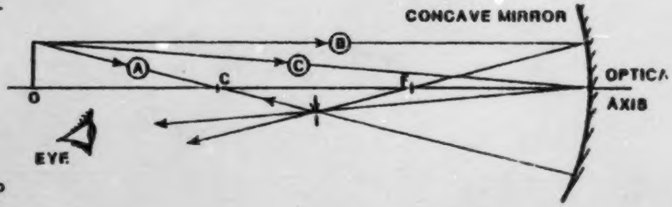


FIG. 5

Ray B, which is parallel to the optical axis, connects the top of the object to a point on the mirror surface. This ray is reflected through focal point F of the concave mirror.

Ray C connects the top of the object to the point of interaction of the optical axis and the mirror surface. Like all rays reflecting from the surface, it is reflected according to the law of reflection.

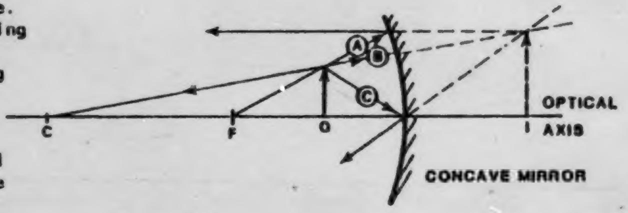


FIG. 6

The point at which all three rays intersect is the top of the image. It is possible to locate the image accurately with only two rays, but three usually are shown. The third may be used as a check.

The image in Figure 5 is called a real image. It is located in front of the mirror surface and, since it is formed by real rays of light, it may be focused on a screen placed at point I. The same real image may also be viewed directly from a point on the optical axis at a greater distance from the mirror than the image itself. (See "eye" in Figure 5.) The light rays entering the eye will diverge from I just as they would if it were a real object.

Figure 6 shows formation of a virtual image when the object is located inside the focal point of a concave mirror. In this instance, ray A, which connects the focal point, the top of the object and a point on the mirror, is reflected parallel to the

MIRROR SHAPES

Although mirrors may be constructed in a wide variety of configurations, the three basic surface shapes most commonly used are considered in this module.

Plane mirrors (Figure 1) have plane reflecting surfaces. When incident parallel light rays strike a plane mirror, angle of incidence A and angle of reflection B are equal, and the same for all rays. Thus, the reflected rays leave the mirror parallel to one another as shown.

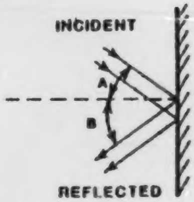


FIG. 1

Figure 2 shows a concave mirror. The optical axis, a line perpendicular to the mirror surface, usually is located at the center of the mirror. Point C is the center of curvature of the mirror surface: distance r is the radius of curvature of the surface.

When light rays parallel to the optical axis strike such a mirror, the equal angles of incidence and reflection are greater near the edge of the mirror than near the center. The reflected rays converge at a point F, called the focal point of the concave mirror. Distance f, from point F to the mirror surface, measured along the optical axis, is called the focal length of the mirror. This focal length is always one half the radius of curvature of the mirror surface (for speherical mirrors).

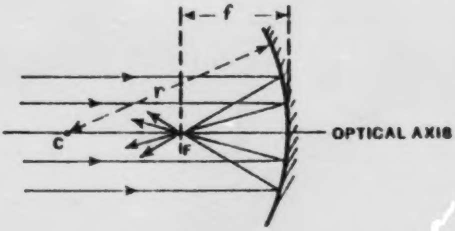


FIG. 2

Figure 3 shows a convex mirror. The optical axis and center of curvature are defined as for a concave mirror. Also, as with the concave mirror, parallel light rays have greater angles of incidence and reflection near the mirror edges. The focal point of a convex mirror is that point from which all reflected rays appear to have originated when parallel rays are incident upon the surface (located by dotted lines behind the mirror). As with the concave mirror, the radius of curvature is twice the focal length.

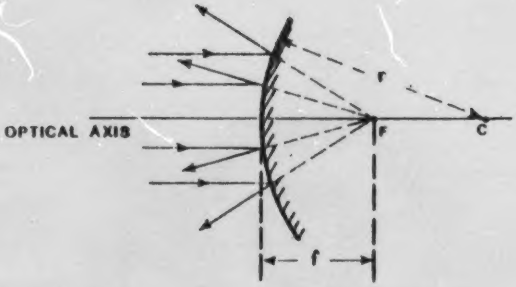


FIG. 3

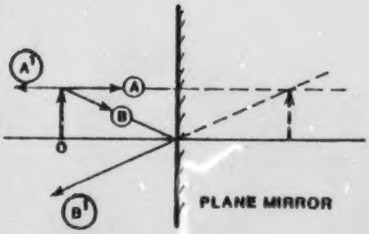


FIG. 4

IMAGE FORMATION

Figure 4 shows the formation of an optical image by a plane mirror. Object O is an arrow with its base on the optical axis. Two light rays are shown leaving the top of the object. Ray A, which is perpendicular to the mirror surface, is reflected back along itself to the top of the object (see A'). Ray B, which strikes the mirror surface on the optical axis, is reflected according to the law of reflection, with the angle of incidence equal to the angle of reflection. The two reflected rays A' and B' diverge as they leave the mirror. If their lines of travel are extended backward past the reflecting surface (dotted lines behind the mirror), they meet to form the top of the image I. The bottom of the image is located on the optical axis.

The image formed behind the reflecting surface is called a virtual image. It may be viewed directly from the front of the mirror, but cannot be focused onto a screen because there is actually no light behind the mirror. This type of image is the only type that can be formed with a plane mirror.

Figure 5 shows the formation of a different type of image by a concave mirror. The three rays used in this figure may always be used to locate images formed by spherical mirrors. They have the following characteristics:

EXAMPLE A: IMAGE DISTANCE WITH CONCAVE MIRROR

Given: Focal length of mirror: $f = 25$ cm; object distance: $p = 75$ cm.

Find: Image distance (is it real or virtual?).

Solution:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

$$\frac{1}{25\text{ cm}} = \frac{1}{75\text{ cm}} + \frac{1}{q}$$

$$\frac{1}{q} = \frac{1}{25} - \frac{1}{75} = \frac{3}{75} - \frac{1}{75} = \frac{2}{75}$$

$$q = \frac{75}{2}$$

$q = 37.5$ cm (a real image if formed because q is positive.)

EXAMPLE B: IMAGE DISTANCE WITH CONVEX MIRROR

Given: Focal length of mirror: $f = -10$ cm; object distance: $p = 25$ cm.

Find: Image distance (is it real or virtual?)

Solution:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

$$\frac{1}{-10\text{ cm}} = \frac{1}{25\text{ cm}} + \frac{1}{q}$$

$$\frac{1}{q} = -\frac{1}{10\text{ cm}} - \frac{1}{25\text{ cm}}$$

$$= -0.1\text{ cm}^{-1} - 0.04\text{ cm}^{-1}$$

$$\frac{1}{q} = -0.14\text{ cm}^{-1}$$

$$\therefore q = \frac{1}{-0.14\text{ cm}^{-1}}$$

$q = -7.14$ cm (virtual image)

Size of the image may be calculated by using Equation 2.

$$h_i = h_o \left(\frac{q}{p}\right) \qquad (2)$$

where

h_i = image height.
h_o = object height.
q = image distance.
p = object distance.

Ratio q/p is the magnification of the image, or h_i/h_o.

The use of Equation 1 is shown in Example C to solve a problem.

EXAMPLE C: IMAGE HEIGHT

Given: The object in Example A is 5 cm high; object distance: $p = 75$ cm; image distance: $q = 37.5$ cm

Find: Image height.

Solution:

$$\begin{aligned} h_i &= h_o \left(\frac{q}{p}\right) \\ &= (5 \text{ cm}) \times \left(\frac{37.5 \text{ cm}}{75 \text{ cm}}\right) \\ &= 5 \text{ cm} \times 0.5 \\ h_i &= 2.5 \text{ cm} \quad \text{(Magnification is 1/2.)} \end{aligned}$$

APPLICATION OF MIRRORS

Mirrors are employed in a wide variety of optical instruments and devices including telescopes, interferometers and lasers. Mirrors also are an essential part of many more common devices. Table 1 lists several mirror applications along with the ray diagram that applies to each application. Information on image distance and type and size of image also is included.

TABLE 1. APPLICATIONS OF IMAGING WITH MIRRORS

Mirror Type	Object Distance	Image Distance	Image Type/Size	Ray Diagram	Application
Plane	Any	$q = -p$ (As far behind as object is in front)	Virtual size of object	Figure 4	Ordinary mirror
Convex	Any	$q < f$	Virtual reduced	Figure 8	Wide-angle rear vision mirror Antitheft mirror in store
Concave	$p = \infty$	$q = f$	Real reduced to point	Figure 2	Solar furnace (parallel incident rays)
Concave	$p = f$	$q = \infty$	None	Figure 2	Spot light (parallel reflected rays)
Concave	$p < f$	$q < 0$	Virtual enlarged	Figure 6	Magnifying mirror
Concave	$f \leq p \leq 2f$	$q \geq 2f$	Real enlarged	Figure 7	Image projection system of large screen television
Concave	$p > 2f$	$2f > q \geq f$	Real reduced	Figure 5	Reflecting telescope

SUMMARY

Mirrors change the direction of light rays by reflection. Plane mirrors reflect parallel incident rays as parallel rays. Concave mirrors reflect parallel rays so that they converge at a point (called the focal point of the mirror). Convex mirrors reflect parallel rays as though they originated at a focal point behind the mirrors' surfaces. The location, type and size of the image produced by a mirror may be determined by drawing two or more rays reflected from the mirror surface according to the law of reflection.

IMAGE FORMATION WITH CONCAVE MIRROR

MATERIALS

Concave mirror 16-inch diameter, 22-inch focal length (Edmund #80,097 or equal).
Piece of wood approximately 1" x 1/4" x 12".
Meter Stick.
Shoe Box.
Tape.
Coin.

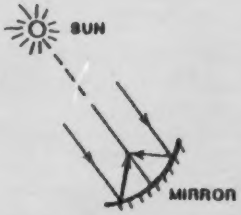


FIG. 9

PROCEDURE

1. Place concave mirror in direct sunlight with optical axis of mirror directed toward sun (Figure 9). CAUTION: Do not place hand or clothing near focal point of mirror.

2. Use piece of wood to locate focal point of mirror. Parallel rays of sun will be focused to smallest spot at focal point. In bright sunlight, wood will burst into flames, demonstrating collection of solar energy. Measure focal length of mirror with meter stick; avoid positioning hand or meter stick at focal point; record focal length in Data Table.

3. Suspend coin inside open end of shoe box; place open end of box in front of mirror, as shown in Figure 10. Top edge of coin is on optical axis; object distance equals radius of curvature (twice focal length).

4. Observe real image produced. Bottom edge of coin is on optical axis. With proper placement of coin, image will appear to stand on edge of box.

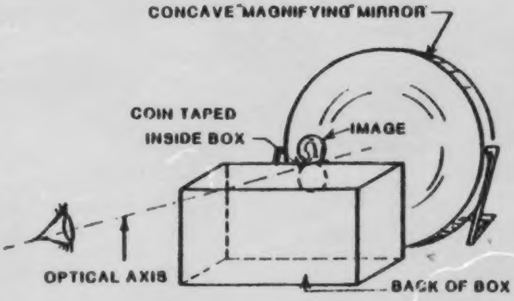


FIG. 10

5. Complete ray diagram of real image formation in Data Table.

6. Hold concave mirror 10 to 12 inches in front of face (Figure 11); observe virtual image formed in mirror.

7. Complete ray diagram of virtual image formation in Data Table.

8. How are real and virtual images utilized in practical applications?

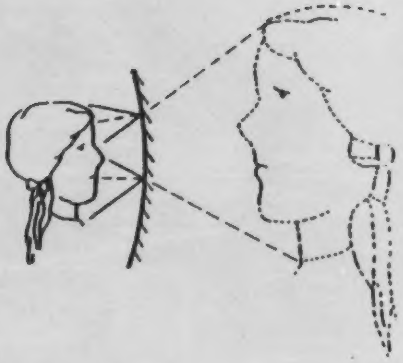


FIG. 11

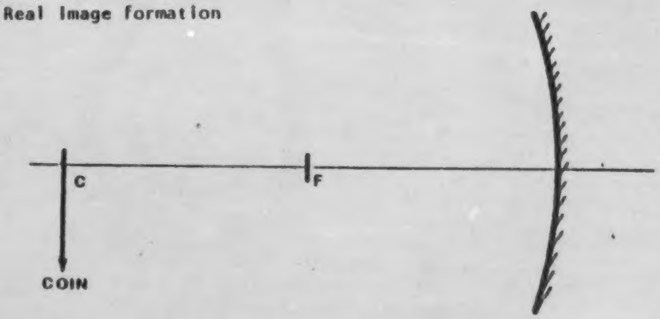
DATA TABLE

Focal length of mirror.

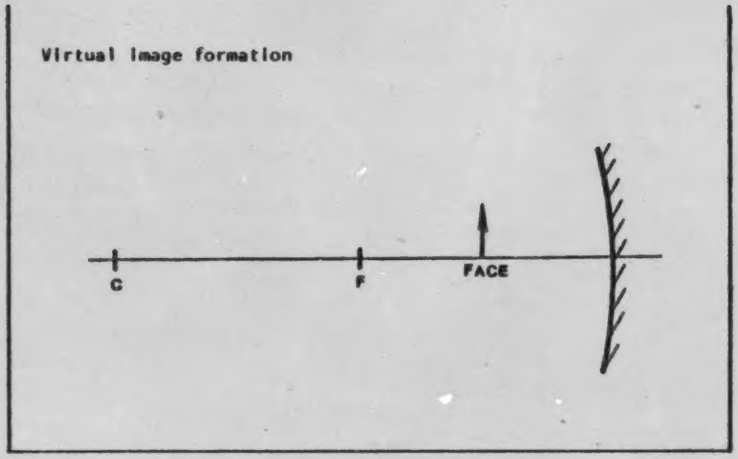
Specified: f = _____

Measured: f = _____

Real image formation



Virtual image formation

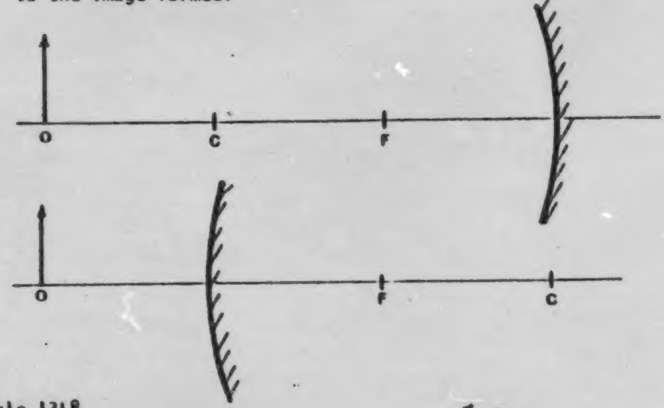


SELF CHECK

1. Describe difference between a real image and a virtual image.

2. Draw diagrams to illustrate the focal points of convex and concave mirrors; show parallel light rays reflected from these mirrors.

3. On the following diagrams, draw three rays from the object to the image formed.



4. A concave mirror has a focal length of 10 cm. An object is located 15 cm from this mirror. Where is the image?

5. The object in problem 4 is 2 cm high. What is the image height?

6. An object is located 10 cm from a mirror. A virtual image is formed 2 cm behind the mirror surface. What is the focal length of the mirror? Is it concave or convex?

7. The image in problem 6 is 0.6 cm high. What is the object height?

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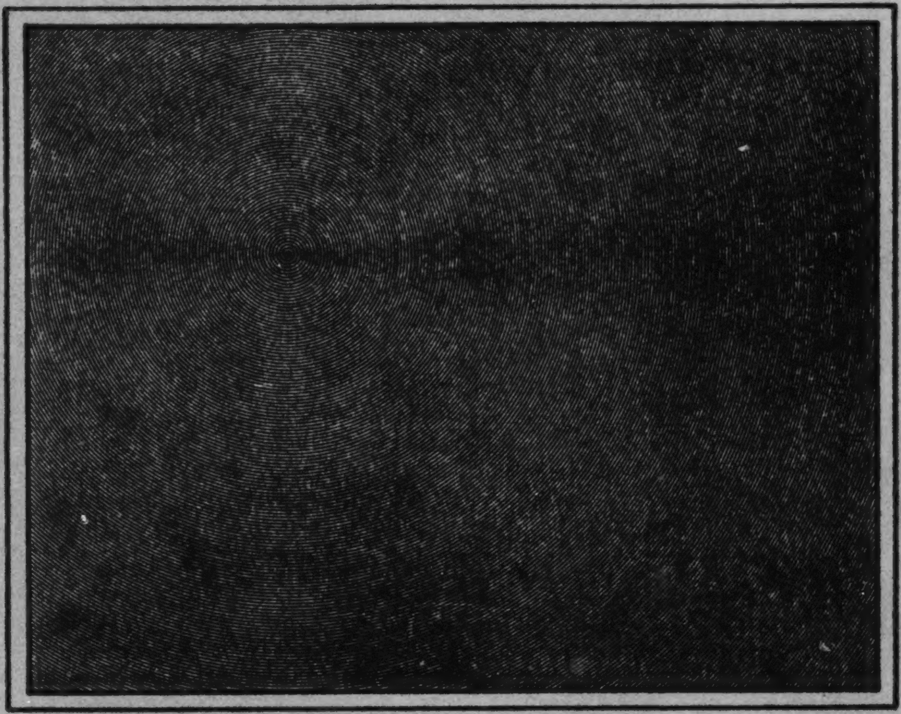
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 9

PRISMS-

REFRACTION AND DISPERSION OF LIGHT



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

In a vacuum, light travels at 3 x 10^8 m/s. When light radiation travels through any transmitting material, its speed always is lower than that in a vacuum. This reduction of speed inside materials is the basis of refraction (bending) of light and of the dispersion (spreading of colors) by prisms. This module presents refraction of light at plane surfaces and a discussion of variations in angle of refraction for different colors of light. In the laboratory, the student will use a prism spectrometer to measure light velocity and index of refraction of a prism at several wavelengths.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13L2, "The Optical Spectrum."

OBJECTIVES

Upon completion of this module, the student should be able to:

- State the equation for the law of refraction, and illustrate with a diagram.
- Given any two of the following quantities, calculate the third:

  Speed of light in a vacuum.
  Speed of light in a material.
  Index of refraction of the material.

- Given any three of the following quantities, calculate the fourth:

  Angle of incidence.
  Angle of refraction.
  Index of refraction of first material.
  Index of refraction of second material.

- Explain total internal reflection in a short paragraph, including a prism as an example.
- Given the appropriate equipment, measure light velocity and index of refraction of a prism at several wavelengths.

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INDEX OF REFRACTION

Figure 1 shows light traveling through a piece of glass. As the light wave enters the glass, it slows down, and its wavelength becomes shorter. When the light leaves the glass, both its speed and wavelength increase to their original values. (Frequency always remains constant.) The index of refraction of a material is the ratio of the speed of light in a vacuum to its speed in that material, as defined by Equation 1.

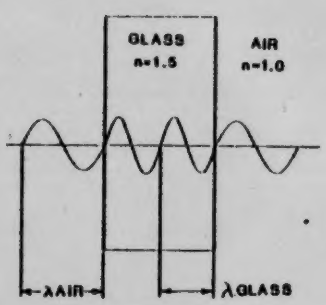


FIG. 1

$$n = \frac{c}{v} \qquad (1)$$

where
n = index of refraction.
c = speed of light in a vacuum.
v = speed of light in material.

The index of refraction of a vacuum is 1, but is greater than one for other materials.

Example A shows the use of Equation 1 in solving a problem.

EXAMPLE A: SPEED OF LIGHT IN A DIAMOND	
Given:	Speed of light in vacuum: $c = 3 \times 10^8$ m/s. Index of refraction of diamond: $n_d = 2.4$.
Find:	Speed of light in a diamond.
Solution:	$v = \frac{c}{n}$ $= \frac{3 \times 10^8 \text{ m/s}}{2.4}$ $v = 1.25 \times 10^8$ m/s

The index of refraction of air may be assumed to be 1.0 for most applications.

REFRACTION OF LIGHT

Refraction is the change in direction of travel of light as it crosses the boundary between two materials.

Figure 2 shows the refraction of light at the surface of a piece of glass. The "normal line" (Figure 2b) is a line perpendicular to the optical surface, and all angles are measured from the normal. Angle A is called the "angle of incidence," and Angle C is called the "angle of refraction." The dashed lines in Figure 2a represent wavefronts (surfaces of constant phase). As the light enters the glass, it slows down, and its wavefronts become closer together and change direction as shown. The direction of travel of the light is "bent" toward the normal according to the law of refraction given in Equation 2.

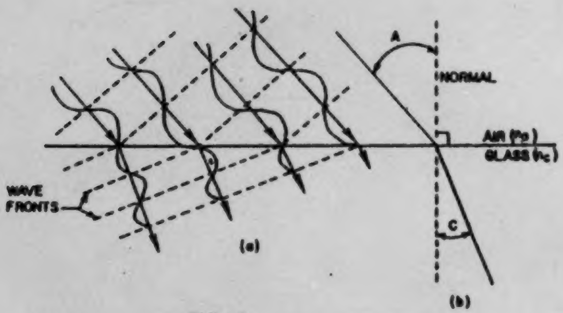


FIG. 2

$$n_a \sin A = n_c \text{ Sin } C \qquad (2)$$

where

n_a = index of refraction of first material.
sin A = sine of angle of incidence.
n_c = index of refraction of second material.
sin C = sine of angle of refraction.

Examples B and C show the use of this equation in solving problems.

EXAMPLE B: ANGLE OF REFRACTION

Given: In Figure 2b angle of incidence: $A = 42°$.
Index of refraction of air: $n_a = 1.0$.
Index of refraction of glass: $n_c = 1.7$.

Find: Angle of refraction C.

Solution: $n_a \sin A = n_c \sin C$

$$(1.0)\sin(42^\circ) = (1.7)\sin C$$

$$(1.0)\times(0.67) = (1.7)\sin C$$

$$\sin C = \frac{(1.0)\ (0.67)}{(1.7)}$$

$$\sin C = 0.394$$

$$C = \sin^{-1}(0.394)$$

$$C = 23.2^\circ$$

EXAMPLE C : REFRACTION BY A PRISM

Given: Light refracted by a 60° prism. The angle of incidence at entrance is 70°, and the angle of refraction is 37°. The angle of incidence at exit is 23°.

Find:
(a) Index of refraction of prism (n_p).
(b) Angle of refraction at exit (F).

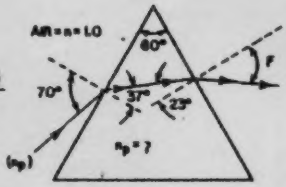
Solution: (a) $n_a \sin A = n_c \sin C$

$$n_c = \frac{n_a \sin A}{\sin C}$$

$$n_p = \frac{(1.0)\sin(70^\circ)}{\sin(37^\circ)}$$

$$= \frac{0.940}{0.602}$$

$$n_p = 1.56$$



(b) $\sin C = \dfrac{n_a \sin A}{n_c}$

$$\sin F = \frac{(1.56)\sin(23^\circ)}{1.0}$$ (See note below.)

$$= \frac{(1.56)(0.391)}{1.0}$$

$$\sin F = 0.610$$

$$F = \sin^{-1}(0.61)$$

$$F = 37.6^\circ$$

Notice that in part b the light is incident upon air from inside the glass prism. Thus: $n_a = 1.56$, $A = 23^\circ$, $n_c = 1.0$, $C = F$.

The refraction of light by prisms has many applications in lighting. Figure 3 shows an ordinary plastic diffuser used in both fluorescent and incandescent light fixtures to produce more even illumination. The tiny prisms change direction of

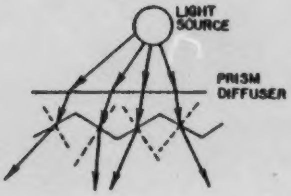


FIG. 3

the light rays and increase apparent size of the light source.

TOTAL INTERNAL REFLECTION

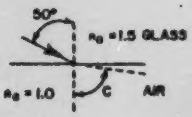
Example D shows what happens when light strikes an air-glass boundary from inside the glass with a high angle of incidence.

EXAMPLE D: TOTAL INTERNAL REFLECTION

Given: Light strikes an air-glass boundary from inside the glass ($n = 1.5$) with an angle of incidence of 50°.

Find: Angle of refraction C.

Solution: $n_a \sin A = n_c \sin C$



$$\sin C = \frac{n_a \sin A}{n_c}$$

$$= \frac{(1.5)\sin(50°)}{(1.0)}$$

$$= (1.5)(0.776)$$

$$\sin C = 1.164$$

Something is wrong, because the sine of an angle can never be greater than 1. This problem cannot be solved by law of refraction. (Refer to next paragraph and to Figure 4.)

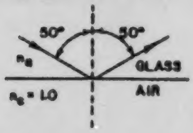


FIG. 4

Figure 4 shows what actually happens in Example D. The light cannot be refracted out of the glass, but experiences total internal reflection at the surface. The greatest angle of incidence for which light can be refracted through a boundary is called the "critical angle," and is given by Equation 3.

$$A_c = \sin^{-1}\left(\frac{n_a}{n_c}\right) \tag{3}$$

where

A_c = critical angle.

$\sin^{-1}$ = arc sine.

If the angle of incidence exceeds the critical angle, all the light is reflected according to the law of reflection discussed in Application Module 13L7, "Specular and Diffuse Reflection of Light." Figure 5 shows how this principle is used in reflective prisms. The plastic reflectors along the sides of roads and on automobiles are composed of many small prisms that reflect light back in the direction from which it came. Road signs are seen easily at night because they are covered with tiny glass beads that serve the same function. Figure 6 shows light reflected by such a glass sphere. In this case, the angle of incidence is less than the critical angle, and some of the light is refracted out of the rear of the sphere.

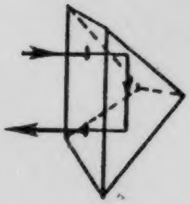


FIG. 5

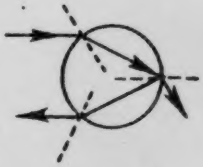


FIG. 6

DISPERSION

Figure 7 shows how a prism separates white light into the visible spectrum by a process called "dispersion." This phenomenon occurs because the index of refraction of materials varies with the wavelength of light, which indicates that different colors (wavelengths) of light have different speeds through a material.

Figure 8 shows dispersion curves for several optical materials. In each case, the index of refraction is highest for shorter wavelengths. Thus, shorter wavelengths (blue light) are refracted to a greater extent than longer wavelengths (red light). The ability of a prism to disperse white light into its component wavelengths is the basis of the prism spectrometer used in the laboratory portion of this module. The same principle is employed in infrared spectrophotometers used for analysis in scientific laboratories

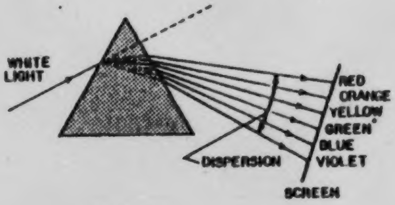


FIG. 7

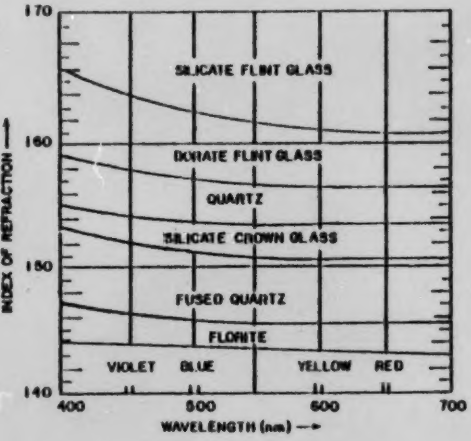


FIG. 8

SUMMARY

Reduction of light speed when passing through a prism is responsible for light refraction (bending) and for light dispersion (spreading of colors). Prisms are used in many reflective materials. Prism and infrared spectrometers disperse white light into its component wavelengths, making visible the various colors.

LIGHT VELOCITY AND INDEX OF REFRACTION OF A PRISM

MATERIALS

Prism spectrometer (Sargent-Welch #S-75903-80 or equivalent consisting of:

- Collimator with slit and lens that allows a small amount of light to strike prism in parallel rays.
- Equilateral prism.
- Telescope with objective lens, eyepiece and cross hairs.
- Vernier scale to allow measurement of angles to the nearest tenth of a degree.

Helium spectrum tube.
Spectrum-tube power supply.

PROCEDURE

1. Set up equipment as shown in Figure 9, but do not place prism on prism stage.

2. Turn on spectrum tube power supply; place spectrometer slit near capillary portion of tube. BEWARE OF HIGH VOLTAGE.

3. Align telescope with collimator; focus telescope to obtain sharp image of slit. Set cross hair on image of slit.

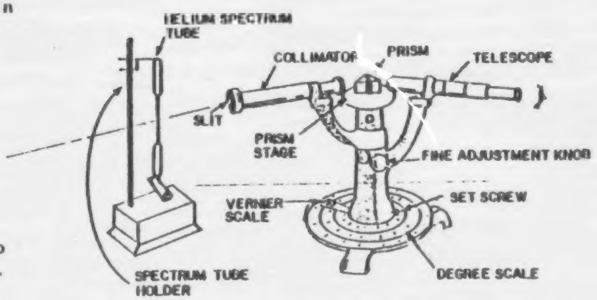

HELIUM SPECTRUM TUBE
COLLIMATOR
PRISM
TELESCOPE
SLIT
PRISM STAGE
FINE ADJUSTMENT KNOB
VERNIER SCALE
SET SCREW
SPECTRUM TUBE HOLDER
DEGREE SCALE

FIG. 9

4. Loosen set screw; move degree scale around until zero on degree scale lines up with zero on vernier scale. Be sure cross hair is on image of slit; tighten set screw.

5. Place prism on stage as in Figure 9. Move telescope to angle of approximately 40°. Helium tube and collimator remain fixed.

6. View spectral lines. Refocus telescope for sharpest image.

7. Rotate prism stage while observing spectrum. Set prism to obtain minimum angle of deviation of light. NOTE: The angle of deviation is the angle measured between the straight line found by the collimator and telescope (step 3) and the telescope position after the prism has been placed on the stage (step 5). This angle can be made a minimum for any line in the helium spectrum viewed with the telescope when the prism is rotated appropriately. Consult instructor if difficulty arises with this setting.

8. Set cross hair on first red line (706.8 nm). Read angle from vernier; record in Data Table.

9. Without moving prism, set cross hair on each bright helium line listed in Data Table; record angle of each.

10. Calculate index of refraction for prism at each wavelength using the following equation (true only at angle of minimum deviation):

$$n = \frac{\sin\left(\frac{A + B}{2}\right)}{\sin\left(A/2\right)}$$

where

A = apex angle of prism (60°).
B = angle of deviation of light.

Record index of refraction to five significant figures.

11. Choose appropriate values for vertical axis of graph (Figure 10) to show variations in index of refraction. Plot data points; connect with a smooth curve.

DATA TABLE			
Helium Spectrum		Angle of Deviation °	Index of Refraction
Color	Wavelength (nm)		
Red	706.8		
Red	667.8		
Yellow	587.6		
Green	504.8		
Blue-green	492.2		
Blue	471.3		
Deep blue	447.1		
Violet	438.8		
Violet	402.6		
Violet	388.6		

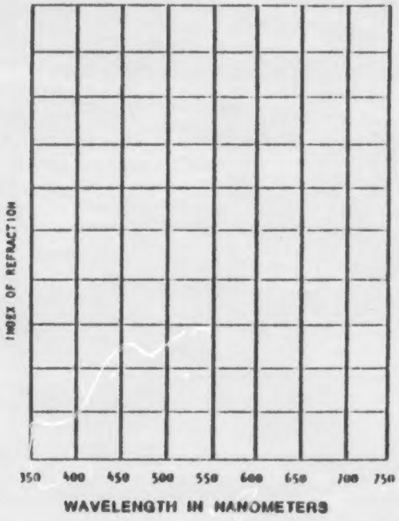


FIG. 10

SELF CHECK

1. Write the equation for the law of refraction.
2. The index of refraction of fused quartz for light with a wavelength of 700 nm is 1.45. What is the speed of light in quartz?
3. Light passes from air into water (n = 1.33) with an angle of refraction of 32°. What is the angle of incidence?
4. Light passes from water (n = 1.33) into flint glass (n = 1.64) with an angle of incidence of 55°. What is the angle of refraction?
5. Draw a sketch showing total internal reflection in a prism.
6. Is the index of refraction of a material greater for red light or blue light?

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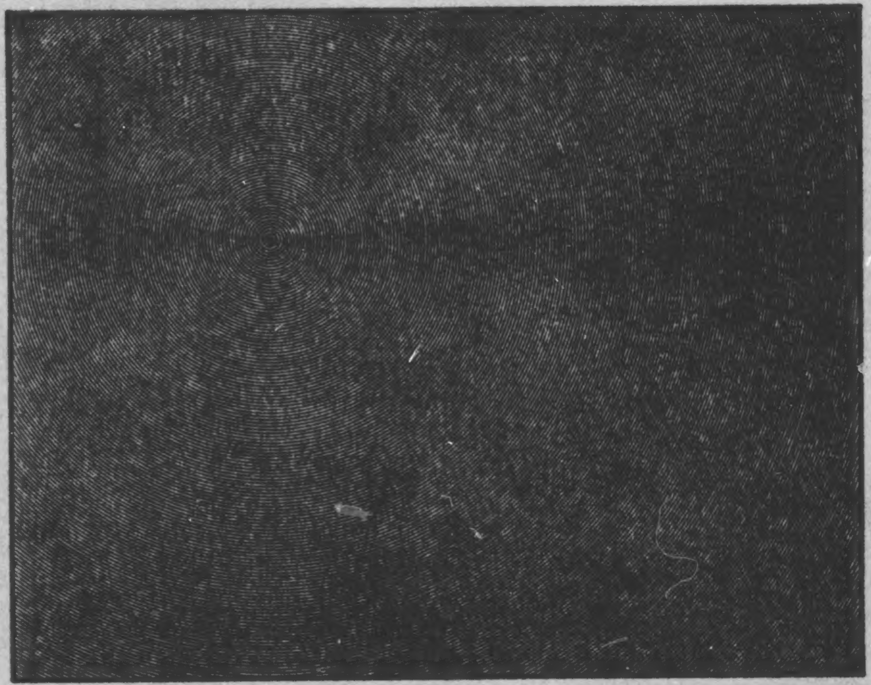
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 10

LENSES

FOCUSING AND SPREADING OF LIGHT



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Lenses are optical devices that change the directionality of light beams by refracting different parts of the beams by differing amounts. This module discusses properties of lenses, formations of real and virtual images by lenses, and a variety of lens applications, including corrective eyewear. In the laboratory, the student will construct a small refracting telescope.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13L9, "Prisms - Refraction and Dispersion of Light."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Draw an appropriate diagram that illustrates each of the definitions of image forming systems given below:

  The focal point of a positive lens.
  The focal point of a negative lens.
  The real image formed by a positive lens.
  The virtual image formed by a positive lens.
  The virtual image formed by a negative lens.

- Give one practical application for each of the above optical arrangements.
- Given any two of the following quantities, calculate the third:

  Focal length of lens.
  Object distance.
  Image distance.

- Given one of the following quantities, calculate the other:

  Focal length of lens.
  Power of lens in diopters.

- Given appropriate equipment, form and describe real and virtual images developed by positive lenses; construct a refracting telescope.

FOCAL POINTS OF LENSES

In Figure 1, parallel rays of light strike a converging (positive) lens. Each ray is refracted at both surfaces of the lens according to the law of refraction (discussed in Application Module 13L9, "Prisms - Refraction and Dispersion of Light"). The rays then converge at point F, the focal point of the positive lens. Distance f, from the center of the lens to the focal point, the focal length of the lens, is a positive quantity for a positive lens. Practical applications of this ray diagram include 1) focusing of the sun's parallel rays or 2) collimating the beam from a laser.

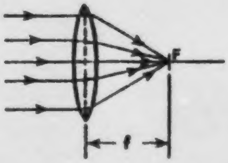


FIG. 1

Figure 2 shows the effect of a diverging (negative) lens on parallel light rays. The lens acts to diverge parallel rays as though they had originated (dashed lines) from a single point F (the focal point of the negative lens). Focal length f of the negative lens is a negative quantity. This ray diagram, which represents the spreading of light rays to cover a larger area, often is used in photographic flash systems.

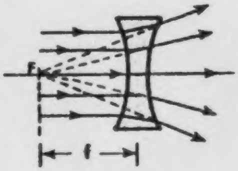


FIG. 2

The focal length of a lens may be measured in any convenient units of length; often, this refractive power of a lens is expressed in "diopters," as expressed in Equation 1.

$$P\ (D) = \frac{1}{f(m)}. \qquad (1)$$

where

P = refractive power in diopters.
f = focal length in meters.

Example A shows how to use Equation 1 in solving a typical problem.

EXAMPLE A: POWER OF A LENS

Given: (a) Focal length of a converging lens is 25 cm.
(b) Power of a diverging lens is -2.5.

Find: (a) Power of converging lens.
(b) Focal length of negative lens.

Solution: (a)

$$P = \frac{1}{f} = \frac{1}{0.25\ \text{m}}$$

$$P = 4.0\ \text{D}$$

(b)

$$f = \frac{1}{P} = \frac{1}{2.5\ \text{D}}$$

$$f = 0.4\ \text{m} = 40\ \text{cm}$$

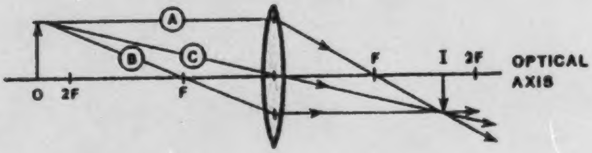


FIG. 3

Figure 3 shows formation of a real image by a positive lens. Object O is at a distance from the lens greater than twice the focal length (2f) of the lens. The following rays are used to locate the image:

Ray A originates at the top of the object and travels parallel to the optical axis. It is refracted to pass through the focal point on the other side of the lens.

Ray B travels through the focal point on the object side of the lens and is refracted to leave the lens in a direction parallel to the optical axis.

Ray C passes through the center of the lens and is undeviated.

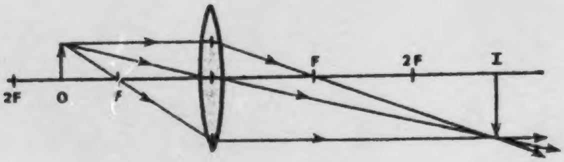


FIG. 4

If the object is located at a great distance from the lens, the image is near the focal point and greatly reduced in size. This optical arrangement applies both to a camera and to the human eye.

Figure 4 shows the image formed by the same lens when the object distance is in the range between the focal length of the lens and twice the focal length. In this instance, the image is enlarged and the image distance is greater than 2f. This ray diagram is representative of the optical arrangements used in movie and slide projectors, where O is the film and I is the screen.

Figure 5 shows the virtual image formed when an object is placed inside the focal point of a positive lens. This virtual image always appears magnified and erect. (Real images formed by lenses always appear inverted.) Virtual, magnified images formed by positive lenses include those displayed by the familiar magnifying glasses, as well as the plastic lenses used to enlarge the display of many pocket calculators.

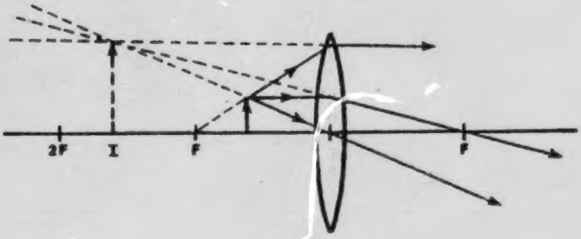


FIG. 5

The virtual image formed by a negative lens is shown in Figure 6. In this diagram, ray A enters the lens parallel to the optical axis (as in the case of the positive lens), and is refracted as though it came from the focal point. Ray B travels toward the focal point on the opposite side of the lens, and is refracted parallel to the optical axis. Ray C passes through the center of the lens and remains undeviated. The virtual image formed is always erect and smaller than the object. Peepholes in doors often are equipped with negative lenses, which provide wide-angle views.

IMAGE LOCATION AND SIZE

Equations for location and size of images formed by lenses are the same as those for mirrors given in Module 13L8, "Image Formation with Mirrors":

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \qquad (2)$$

where

f = focal length.
p = image distance.
q = object distance.

$$h_i = h_o \left(\frac{q}{p}\right) \qquad (3)$$

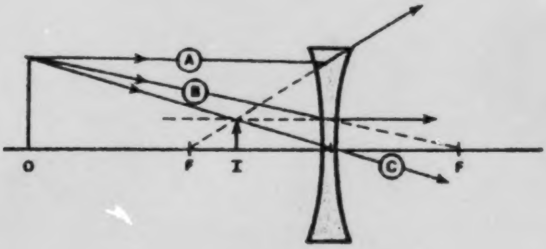


FIG. 6

where

h_i = image height.
h_o = object height.
q = image distance.
p = object distance.

The ratio q/p is the magnification of the lens. Equation 3 shows that this is the same as the ratio of image size to object size, or h_i/h_o.

Examples B and C illustrate the use of Equations 2 and 3 in solving problems.

EXAMPLE B: IMAGE OF A CONVERGING LENS

Given: Focal length of lens: $f = 10$ cm; object distance: $p = 25$ cm; object height: 3 cm.

Find: Image distance and height.

Solution: Image distance =

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

$$\frac{1}{10\text{ cm}} = \frac{1}{25\text{ cm}} + \frac{1}{q}$$

$$0.1\text{ cm}^{-1} = 0.04\text{ cm}^{-1} + \frac{1}{q}$$

$$\frac{1}{q} = 0.06\text{ cm}^{-1}$$

$$q = \frac{1}{0.06\text{ cm}^{-1}}$$

$$q = 16.67\text{ cm}$$

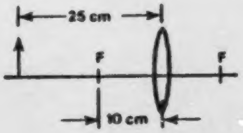


Image height =

$$h_i = h_o \times \left(\frac{q}{p}\right)$$

$$= 3.0\text{ cm} \times \left(\frac{16.67\text{ cm}}{25\text{ cm}}\right)$$

$$h_i = 2.0\text{ cm}$$

Magnification of lens = $h_i/h_o = 2/3 = q/p = 16.67/25$

EXAMPLE C: IMAGE OF A DIVERGING LENS

Given: Object distance: $p = 10$ cm; object height: $h_o = 3.5$ cm; virtual height: $h_i = 0.625$ cm.

Find: Image distance and focal length of lens.

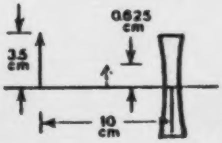
Solution: Image distance=

$$h_i = h_o \left(\frac{q}{p}\right)$$

$$q = p \left(\frac{h_i}{h_o}\right)$$

$$q = (10 \text{ cm}) \times \left(\frac{0.625 \text{ cm}}{3.5 \text{ cm}}\right)$$

$$q = 1.79 \text{ cm}$$



Focal length =

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

$$= \frac{1}{10 \text{ cm}} + \frac{1}{(-1.79 \text{ cm})}$$

Image distance of virtual image is negative.

$$= 0.1 \text{ cm}^{-1} - 0.559 \text{ cm}^{-1}$$

$$= -0.459 \text{ cm}^{-1}$$

$$\therefore f = \frac{1}{-0.459 \text{ cm}^{-1}}$$

$$f = -2.18 \text{ cm}$$

LENS COMBINATIONS

Many optical systems consist of several lenses in combination. Figure 7 shows a fifteen-element lens system, such as a zoom lens for a movie camera. Figure 8a shows proper focusing of parallel light rays by an eye; Figure 8b shows focusing of parallel light by a nearsighted (myopic) eye; Figure 8c shows that of a farsighted (hyperopic) eye. In Figure 9 corrections for myopia (9a) and hyperopia (9b) are achieved by adding the appropriate correcting lens to an optical system.

Figure 10 shows the locations of images in a microscope. The objective lens forms a real image of object A at point B. This real image serves as the object of the eyepiece lens, which forms a virtual image at C. The lens of the eye, which uses the virtual image at C as an object, focuses a real image on the retina at D.

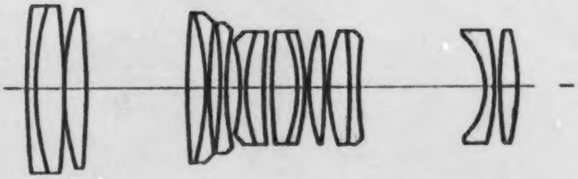


FIG. 7

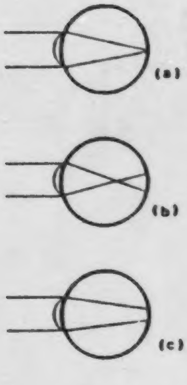


FIG. 8

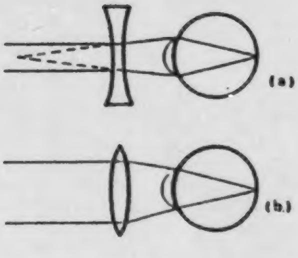


FIG. 9

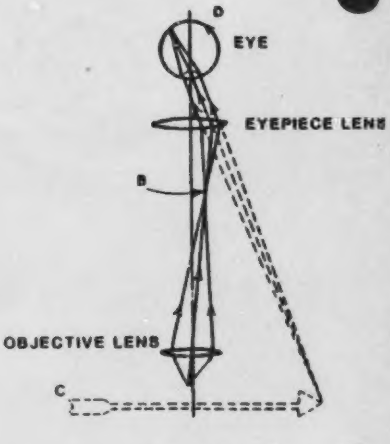

D
EYE
EYEPIECE LENS
B
OBJECTIVE LENS
C

FIG. 10

SUMMARY

A lens changes the directionality of a light beam by refracting different parts of the beam through differing angles. A converging (positive) lens is one that causes parallel incident rays to converge to a point (called the focal point of the lens). A diverging (negative) lens is one that causes parallel rays to diverage as though they originated from the focal point. The size, type and location of an image formed by a lens may be determined by drawing two or more rays through the lens.

LABORATORY

IMAGE FORMATION WITH LENSES

MATERIALS

Refractor telescope kit (Edmund #71,473 or equivalent) consisting of:

- Objective lens.
- Eyepiece lens.
- Glare stops.
- Cardboard tubes.
- End caps.
- Instructions for assembly.

Incandescent light bulb.
White screen.

PROCEDURE

1. Set incandescent bulb and screen 1 meter apart on level surface (Figure 11).

2. Hold objective lens (larger-diameter lens) near screen and perpendicular to light rays from bulb; move lens toward bulb until sharp image is formed on screen.

3. Measure image (q) and object (p) distances; record in Data Table.

4. Complete Data Table under "Objective Lens" to determine focal length of objective lens.

5. Repeat above procedure for eyepiece lens.

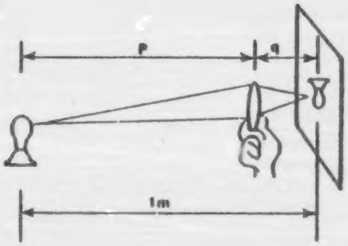


FIG. 11

6. Assemble telescope according to directions with telescope kit.

7. View virtual images of distant objects formed by telescope.

8. Complete ray diagram of telescope in Data Table below.

DATA TABLE

Objective lens

Object distance: $p = \_\_\_\_\_\_$ cm.

Image distance: $q = \_\_\_\_\_\_$ cm.

Focal length: $\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$

$$= \frac{1}{\_\_\_\_\_\_\text{ cm}} + \frac{1}{\_\_\_\_\_\_\text{ cm}}$$

$$= \_\_\_\_\_\_\text{ cm}^{-1} + \_\_\_\_\_\_\text{ cm}^{-1}$$

$$= \_\_\_\_\_\_\text{ cm}^{-1}$$

$$f = \frac{1}{\_\_\_\_\_\_\text{ cm}^{-1}}$$

and $f = \_\_\_\_\_\_$ cm

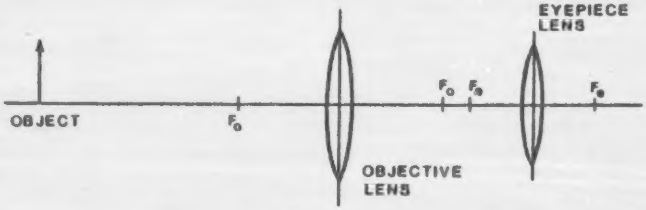
Eyepiece lens

Object distance: $p = \_\_\_\_\_\_$ cm

Image distance: $q = \_\_\_\_\_\_$ cm

Focal length: $f = \_\_\_\_\_\_$ cm

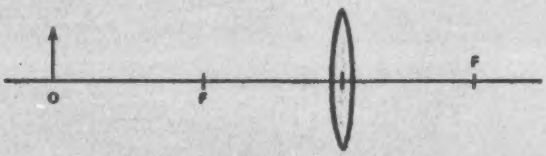
Ray diagram of a telescope:


EYEPIECE LENS
OBJECT
F_o
F_o
F_e
F_e
OBJECTIVE LENS

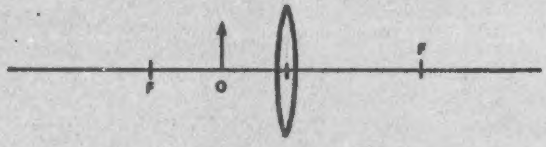
SELF CHECK

1. Complete the following ray diagrams to show the image formed.

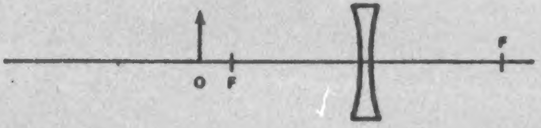
a.



b.



c.



2. Sketch the lens, object and image in each of the following optical systems:

   a. Magnifying glass.
   b. Movie projector.
   c. Camera.

3. The focal length of a peephole lens in a door is -2.0 cm. A person 6 feet tall stands 3 m from the lens; find the image distance and height.

4. A slide projector lens has an object distance of 8.5 cm and an image distance of 2.3 m. What is its focal length?

5. What is the focal length of a lens with a power of 10 diopters?

6. What is the power in diopters of a lens with a 2.5 cm focal length?

REFERENCES

Jenkins, Francis A. and White, Harvey E. Fundamentals of Optics.
New York: Mc-Graw Hill Book Company, 1957.

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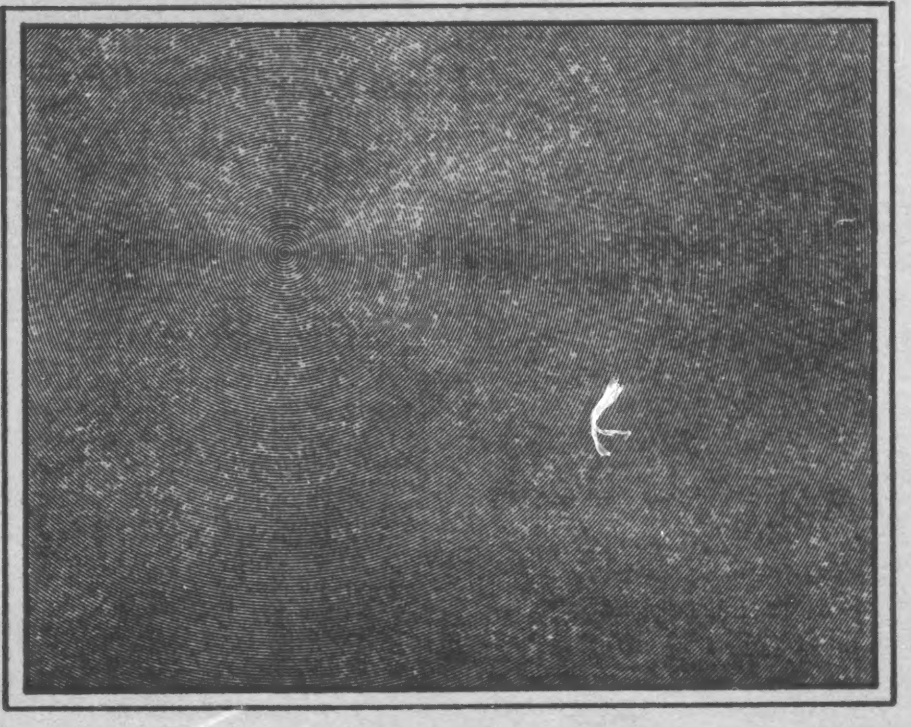
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 11

INTERFERENCE-TESTING FLAT SURFACES



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

The interference of light waves is a description of the way in which light radiation interacts with itself. If two light waves are in phase at a point on a screen, a bright spot is produced. If the two waves are completely out of phase, a dark area results. The alternating light and dark fringes of such an interference pattern can provide useful information. This module discusses the interference of light waves and one method of using this phenomenon for highly-accurate measurement of the flatness of surfaces. In the laboratory, the student will produce air-wedge interference patterns.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Modules 13L1, "Inverse Square Law — Spreading of Light," and 13L7, "Specular and Diffuse Reflection of Light."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Draw and itentify diagrams that illustrate constructive and destructive interference of waves.
- Draw and identify a diagram that depicts the light paths for the constructive and desctructive interference of light waves reflected from an air wedge.
- Given the wavelength of light and the spacing of the fringes produced by an air wedge, calculate the wedge angle.
- Illustrate the interference pattern formed when each of the following is placed on a flat surface:

  Another flat surface at a small wedge angle.

  Another flat surface at a large wedge angle.

  A spherical surface.

- Given the appropriate equipment, produce and sketch air-wedge interference patterns.

DISCUSSION

Figure 1a depicts two light waves with their electric fields in phase, arriving at a point on the screen. The two electric fields add together to form a resultant wave (dashed line), of which the amplitude is the sum of the amplitudes of the component waves. The irradiance in Figure 1a is four times the irradiance produced by one wave alone, because irradiance increases with the square of the amplitude of the electric field. This process is called "constructive interference," which results in a bright spot of light.

Figure 1b illustrates destructive interference. In this figure, two light waves arrive exactly out of phase, and their electric fields cancel to produce a dark spot. Interference actually is a redistribution of the optical energy present. That energy missing in the destructive interference areas (dark) appears in the constructive interference areas (bright).

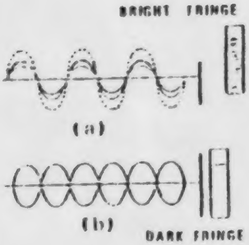

BRIGHT FRINGE
(a)
(b)
DARK FRINGE

FIG. 1

INTERFERENCE PATTERNS

Figure 2 shows how a pattern of light and dark areas (called an "interference pattern") can be produced. Two flat pieces of glass are separated by a thin air wedge and illuminated by a monochromatic (single-color) light source. Under the proper conditions, a series of light and dark bands, called "fringes," will be visible to an observer looking down onto the glass plates.

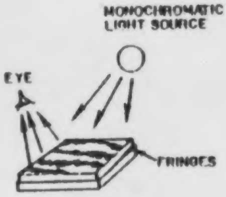

MONOCHROMATIC LIGHT SOURCE
EYE
FRINGES

FIG. 2

Figure 3 indicates how the interference pattern is formed. This figure shows the air wedge between the two pieces of glass and the reflections from the two glass surfaces. Each surface reflects only about four percent of the light striking it; so the patterns produced are dim and must be viewed against a dark background. In Figure 3a, the reflection from the upper and lower surfaces on the air wedge reach the eye exactly out of phase, to create a dark fringe. In Figure 3b, the two waves are reflected in phase to produce a light fringe. These two conditions alternate across the glass, to produce a series of light and dark fringes.

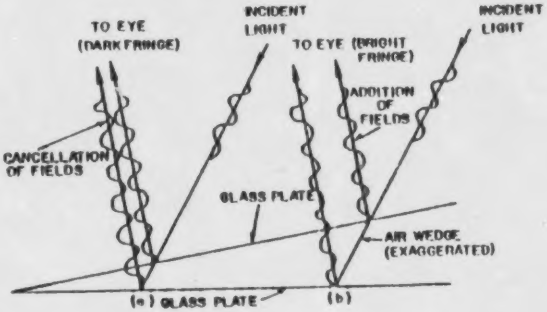

TO EYE (DARK FRINGE)
INCIDENT LIGHT
TO EYE (BRIGHT FRINGE)
INCIDENT LIGHT
ADDITION OF FIELDS
CANCELLATION OF FIELDS
GLASS PLATE
AIR WEDGE (EXAGGERATED)
(a) GLASS PLATE
(b)

FIG. 3

Figure 4 represents two adjacent, bright fringes produced by an air wedge. The thickness of the wedge in Figure 4a is t; therefore, the wave reflected from the lower surface traves 2t farther than the wave reflected from the upper surface. At Figure 4b, the thickness of the wedge has increased by one-half the wavelength of the light used ($\lambda/2$), which means that the path length of the lower wave has increased by an amount equal to the wavelength of the light. Thus, the two reflected waves once again are in phase for constructive interference. Halfway between these two points, the two waves are out of phase, producing destructive interference. The wedge angle of such an air wedge can be calculated from Equation 1.

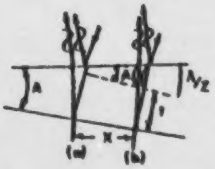


FIG. 4

$$A = \frac{\lambda}{2x} \qquad (1)$$

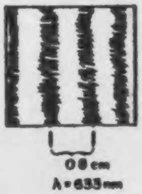
where

A = wedge angle in radians.
λ = wavelength of light.
x = fringe spacing.

The fringe spacing x is the linear distance between the center of one bright fringe and the center of the next bright fringe, or from dark fringe to dark fringe. Example A, shows how this equation is used in solving a problem.

EXAMPLE A: WEDGE ANGLE CALCULATION

Given: An interference pattern exhibits a fringe spacing of 0.8 cm. The wavelength of light is 633 nm.



Find: Angle of air wedge producing fringe pattern.

Solution:

$$A = \frac{\lambda}{2x}$$

$$= \frac{6.33 \times 10^{-7}\ \mathrm{m}}{(2)(8 \times 10^{-3}\ \mathrm{m})}$$

$$A = 3.96 \times 10^{-5}\ \mathrm{rad.}$$

FLATNESS OF OPTICAL SURFACES

The technique described in this module commonly is used to determine the flatness of optical surfaces by comparing them with a surface of known flatness, called a "master," or "standard." If the master is truly flat, the interference pattern produced by placing the unknown surface in contact with the master surface is a contour map of the air space between the two and, therefore, is a reliable indication of the shape of the unknown surface. This procedure is demonstrated in Figures 5 through 9. In each case, the lower reflecting surface is the master flat.

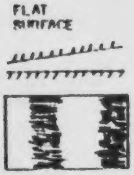


FIG. 5

If both surfaces are flat, the interference pattern will be a series of straight, regularly-spaced fringes. Broad fringes (Figure 4) indicate a small angle between the surfaces, and fine fringes (Figure 5) indicate a larger angle; but both of these patterns signify a flat surface.

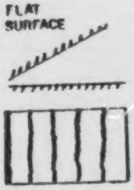


FIG. 6

Figure 7 shows the concentric pattern of rings, called "Newton's rings," resulting from a spherical surface in contact with a flat surface.

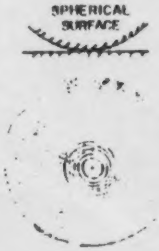


FIG. 7

In Figure 8 a cylindrical surface rests on a plane surface. The cylinder is flat in one direction to produce straight fringes, but is curved in the other direction to produce a variable fringe width and spacing.

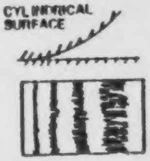


FIG. 8

Figure 9 shows the interference pattern produced by an irregular glass surface, such as a microscope slide.

The procedure explained in the laboratory portion of this module is a standard test procedure used to test surface flatness of optical and machined surfaces. The interference of light is also used by a class of devices called "interferometers" to make measurements on optical components and systems. All interferometers function by splitting a light beam into two or more components, which travel along different paths and are recombined, forming an interference pattern. One such device, termed the "Michaelson interferometer," is displayed in Figure 10. This device is used to measure variations in thickness of an optical component by transmitted light.

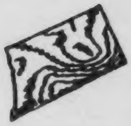


FIG. 9

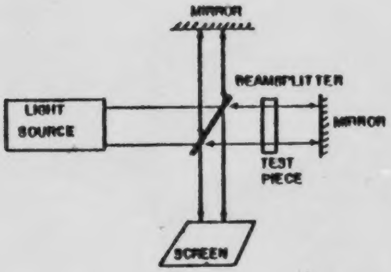


FIG. 10

SUMMARY

The interference of light waves makes possible extremely sensitive methods of testing the optical flatness of a surface (flatness compared with the wavelength of optical radiation, or visible light). The alternating light and dark fringes of interference patterns provide useful information about the surface dimensions of an object. Constructive interference produces bright lines; destructive interference, dark lines. If both the surface tested and the "master" are exactly flat (when the air wedge system is used), the pattern will consist of straight, evenly-spaced fringes.

AIR-WEDGE INTERFERENCE PATTERNS

MATERIALS

Mercury lamp with stand.
Dark green plastic filter.
1-foot square of black felt.
4" x 5" piece of ground glass with mount.
2-inch diameter optical flat, flatness of λ/10 (Edmund #1914 or equivalent).
Piece of flat glass.
Positive lens, focal length 1 m or greater.
Piece of plate glass.
Microscope slide.
Metric scale.

PROCEDURE

1. Set up equipment as shown in Figure 11. Be sure that all optical surfaces are clean and free of dust.

2. Look at flat glass from an angle to allow reflections of ground glass surface to enter eye. Focus eye on air wedge. Move flat glass until fringes are visible. Observe interference pattern; sketch in Data Table.

3. Repeat above procedure for positive lens, plate glass, and microscope slide.

4. Return flat glass to optical flat; obtain a fringe pattern.

5. Measure fringe spacing.

6. Complete Data Table.

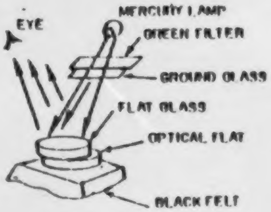


FIG. 11

DATA TABLE

Sketch the interference pattern produced by each surface; state what it reveals about that surface.

Flat glass:

Positive lens:

Plate glass:

Microscope slide:

CALCULATION OF WEDGE ANGLE:

Fringe spacing: $x = \_\_\_\_$ cm $= \_\_\_\_$ m

Wavelength of light: $\lambda = 546$ nm $= \_\_\_\_$ m

Wedge angle: $A = \frac{\lambda}{2x}$

$= \frac{\_\_\_\_\ \text{m}}{2(\_\_\ \text{m})}$

$= \_\_\_\_$ rad

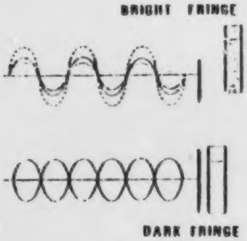
SELF CHECK

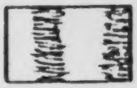
1. Indentify the adjoining sketches as constructive or destructive interference.

2. Draw and identify a diagram showing constructive and destructive interference of light reflected from air wedge between two glass surfaces.

3. Light from a helium-neon laser (λ = 633 nm) is used to illuminate an air wedge. Fringe spacing is 0.025 cm. Calculate the wedge angle.

4. Identify the type of surface that would produce each of the following interference patterns if placed in contact with a flat surface:

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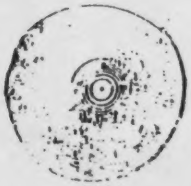
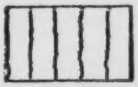
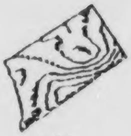

(b)


(c)


(d)

__________ __________ __________ __________

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Technical Education Research Center - Southwest, ed. "Wave Properties of light." Module 1-3, Laser/Electro-Optics Series. Waco, TX; TERC-SW, 1976.

Williams, Charles S. and Becklund, Orville, A. Optics: A Short Course for Engineers and Scientists. New York: Wiley-Interscience, 1972.

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UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 12

DIFFRACTION GRATING -
MEASURING THE WAVELENGTHS OF LIGHT

LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Modern scientific investigation depends greatly on the analysis of light for its data. One of the most important characteristics of light is its wavelength. A diffraction grating is an optical device that separates light into its component wavelengths for application or measurement. This module discusses the phenomenon of diffraction of light and its application in diffraction grating; a diffraction grating spectroscope will be used to measure the wavelength of light in the laboratory.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," Application Module 13L2, "The Optical Spectrum," Application Module 13L9, "Prisms - Refraction and Dispersion of Light," and Application Module 13L11, "Interference - Testing Flat Surfaces," and should be familiar with basic trigonometry.

OBJECTIVES

To complete this module, the student should be able to:

- Summarize Huygens' principle, in one or two sentences.
- Draw and label a diagram showing diffraction of waves at an edge barrier, including the edge barrier, shadow and wavefronts.
- Draw and label a diagram showing the intensity pattern resulting from double-slit diffraction, including intensity, orders of diffraction, distance, single-slit diffraction envelope and double-slit diffraction peaks.
- Given any two of the following quantities, calculate the third:

    Wavelength of light.
    Diffraction angle of a specific order.
    Grating spacing.

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- Given appropriate equipment, measure the wavelength of light with a grating spectroscope.

DISCUSSION

Huygens' principle is used to predict the shape and position of a defined wavefront of light after it has traveled a given distance. It states that each point on a wavefront may be considered to be the source of a spherical wavelet. The new shape and position of the wavefront at any time is a line tangent to all the wavelets at that instant as shown for a spherical wavefront in Figure 1.

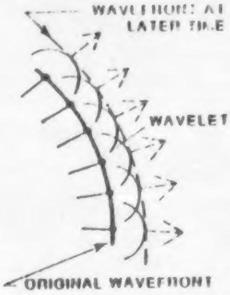

FIG. 1

Figure 2 shows this principle applied to a plane wavefront striking an edge barrier. Part of the wave bends around the edge of the barrier, then it travels into the area of the geometric shadow. This action is most easily observed for water waves, but is also true of all other waves, including light. This bending of a wave around an edge is called diffraction.

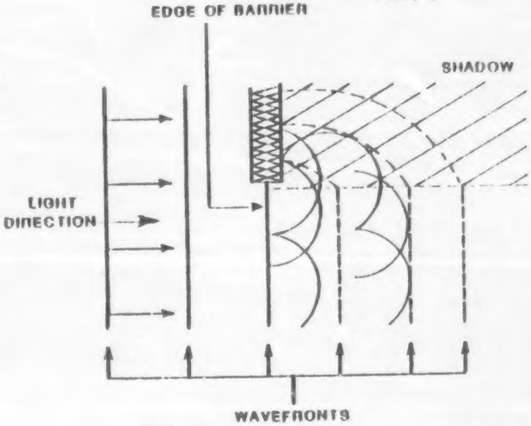

FIG. 2

Figure 3 shows plane wavefronts of light striking a narrow slit. The distance x to the screen is much greater than slit width b. The slit has been divided into several small segments; each segment is the source of a Huygens' wavelet. At point D, the wavelets from all slit segments are in phase, and constructive interference occurs to produce a bright area. At point E, the waves from A and C are in phase, but both are out of phase with other waves, for example, from B. The resulting destructive interference of all waves at point E produces a dark area. The intensity pattern produced on the screen (also shown in Figure 3) is called a single-slit diffraction pattern.

Figure 4 shows light waves diffracted through two slits. The arrows indicate lines along which the waves from the two slits are in phase (wavefronts intersect). Figure 5 is a diagram of double-slit diffraction. For point P to be a bright fringe, waves from the two slits must arrive in phase. For this event to occur, the difference in

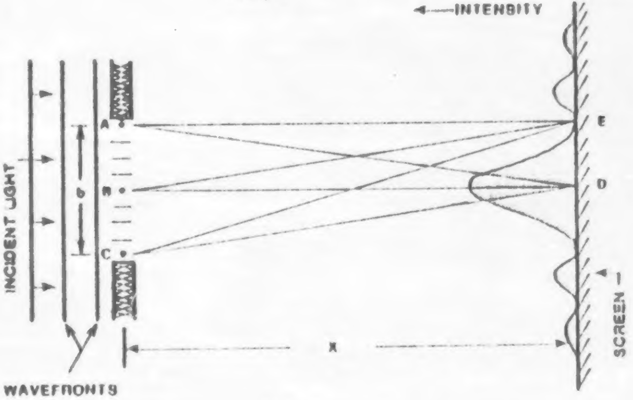

FIG. 3

optical path length for the two waves must be equal to an integral multiple of the wavelength of light. For this distance, d sin θ in Figure 5, d is the slit separation and θ is the angle of diffraction, which leads to Equation 1:

$$d \sin \theta = m\lambda \tag{1}$$

where
d = slit separation.
θ = angle of diffraction.
λ = wavelength of light.
$m = 0, 1, 2, 3 \ldots$

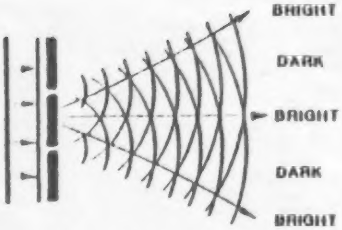

FIG. 4

This equation gives the angular location of the bright finges of a double-slit diffraction pattern. Figure 6 shows the intensity pattern resulting from double-slit diffraction. The envelope of the pattern (dashed line), which is the single-slit diffraction pattern, depends on the width of the slits. Each of the narrower peaks represents a point at which Equation 1 is satisfied for constructive interference between the two slits, and depends on their separation. Numbers in the circles are values of m (in the equation) for each peak, called "orders of diffraction." These numbers represent the whole wavelengths by which the optical path length of one slit differs from that of the other slit.

Figure 7 shows a diffraction grating consisting of a large number of slits, each with a fixed width and spacing. Equation 1 also is true for the diffraction grating. Increasing the number of slits does not change the spacing of the diffraction pattern in Figure 6, as long as d remains fixed; however, increasing the

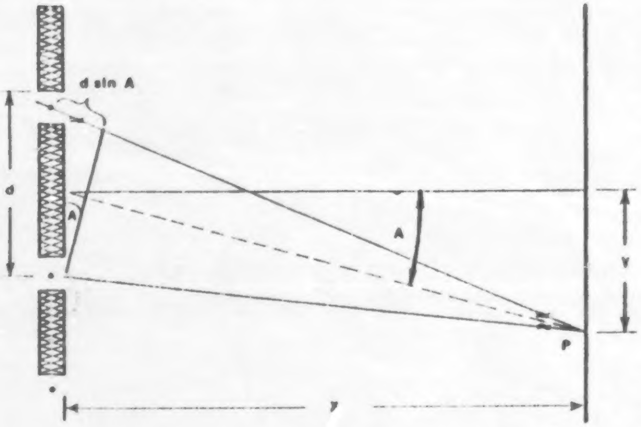

FIG. 5

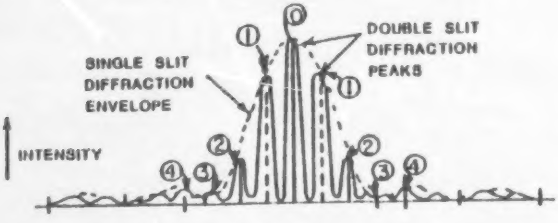

FIG. 6

number does decrease the width of peaks in the double-slit pattern, making separation of different wavelengths easier.

Figure 8 shows white light striking a diffraction grating with its slits perpendicular to the plane of the page. The zero order is undiffracted white light. On each side of this order are the higher orders of diffraction. In each order, red light is diffracted through a larger angle than blue light. Example A shows how data taken with a diffraction grating may be used to determine the wavelength of light by using Equation 1.

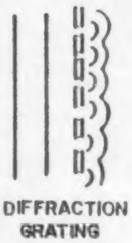
DIFFRACTION
GRATING

FIG. 7

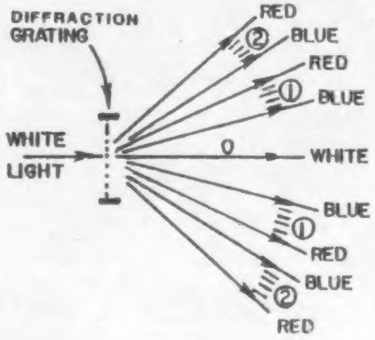
DIFFRACTION
GRATING
WHITE
LIGHT
RED
②
BLUE
RED
①
BLUE
0
WHITE
BLUE
①
RED
BLUE
②
RED

FIG. 8

EXAMPLE A: CALCULATING WAVELENGTH OF LIGHT

Given: In Figure 8 the first order diffraction angle for red light from a helium-neon laser is 19.5°; the grating spacing is $d = 1.896 \times 10^{-6}$ m (13,400 lines/inch).

Find: Wavelength of laser light.

Solution: $d \sin \theta = m\lambda$

$$\lambda = \frac{d \sin \theta}{m}$$

$$= \frac{(1.896 \times 10^{-6} \text{ m})}{1} \times \sin (19.5°)$$

$$= (1.896 \times 10^{-6} \text{ m}) \times (0.3338)$$

$$= 6.33 \times 10^{-7} \text{ m}$$

$$\lambda = 633 \text{ nm.}$$

Examples B and C shown the solution to additional problems using this equation.

EXAMPLE B: DIFFRACTION ANGLE CALCULATION

Given: Grating spacing $d = 1.896 \times 10^{-6}$ m; wavelength of light $\lambda = 488$ nm (blue).

Find: First order diffraction angle.

Solution:

$$d \sin \theta = m$$

$$\sin \theta = \frac{m\lambda}{d}$$

$$= \frac{(1) \times (4.88 \times 10^{-7} \text{ m})}{(1.896 \times 10^{-6} \text{ m})}$$

$$= 0.2574$$

$$\theta = \sin^{-1} (0.2574)$$

$$\theta = 14.9°.$$

EXAMPLE C: CALCULATION OF GRATING SPACING

Given: Second order diffraction angle A = 37.72°; wavelength of light $\lambda = 580$ nm.

Find: Grating spacing.

Solution:

$$d \sin\theta = m\lambda$$

$$d = \frac{m\lambda}{\sin\theta}$$

$$= \frac{(2) \times (5.80 \times 10^{-7}\ \text{m})}{\sin(37.72°)}$$

$$= \frac{1.16 \times 10^{-6}\ \text{m}}{0.6118}$$

$$d = 1.896 \times 10^{-6}\ \text{m}.$$

Figure 9 shows a reflection grating. Instead of a series of slits, this type of grating is composed of a series of reflective surfaces. Reflection gratings have much higher efficiency than transmission gratings because little light is absorbed. Angle B of the reflecting surfaces, with respect to the grating surface, is chosen to reflect the maximum amount of light in a particular direction. This angle is called the "blaze angle" of the grating.

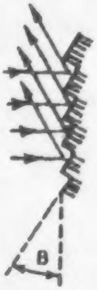

FIG. 9

Research grade gratings are designed to give the best diffraction efficiency for a particular wavelength of light in a particular order of diffraction. A number of optical instruments employing diffraction gratings are discussed in Application Module 13L15, "Spectroscopy - Analysis of Light."

SUMMARY

Diffraction is the bending of a light wave around the edge of obstacle, which causes a portion of the light energy to appear in the region of the geometric shadow. When light passes through two closely spaced, narrow slits, the diffracted light forms two sets of spherical wavefronts that interfere with one another to produce a pattern of light and dark on a screen. Location of the areas of maximum brightness depends on the separation of the slits and the wavelength of light. A diffraction grating, which consists of a large number of slits or reflecting planes, may be used to make highly accurate measurements of the wavelengths of light.

MEASURING THE WAVELENGTH OF LIGHT WITH A DIFFRACTION GRATING

MATERIALS

Grating spectrometer (Sargent-Welch #S-75903-80 or equivalent) consisting of the following components:

- Collimator with slit and lens that allows a small amount of light to strike grating in parallel rays.
- Transmission-type diffraction grating with known spacing.
- Telescope with objective lens, eyepiece and cross hairs.
- Vernier scale to allow measurement of angles to nearest tenth of a degree.

Helium spectrum tube.

Sprectrum tube power supply.

PROCEDURE

1. Record grating spacing in Data Table.
2. Set up equipment as shown in Figure 10, but do not place grating on stage.
3. Turn spectrum tube power supply on; place spectrometer slit near capillary portion of tube. Beware of high voltage.
4. Align telescope with collimator; focus telescope to obtain sharp image of slit; set cross hair on image of slit.
5. Loosen set screw; move degree scale around until zero on degree scale lines up with zero on vernier scale; be sure cross hair is on image of slit; tighten set screw.

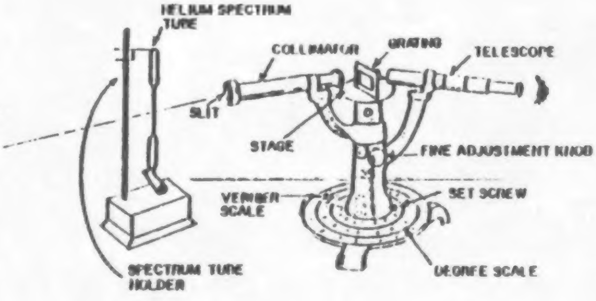
HELIUM SPECTRUM TUBE
COLLIMATOR
GRATING
TELESCOPE
SLIT
STAGE
FINE ADJUSTMENT KNOB
VERNIER SCALE
SET SCREW
DEGREE SCALE
SPECTRUM TUBE HOLDER

FIG. 10

6. Place grating on stage, as shown in Figure 10, with rulings vertical and grating surface perpendicular to incident light; move telescope around until spectral lines (first order) are visible.

7. View spectral lines; refocus telescope; adjust slit width for sharpest image.

8. Set cross hairs on first violet line; read angle from vernier; record in Data Table.

9. Set cross hairs on a total of five strong lines in helium spectrum; record angle of diffraction for each.

10. Continue to move telescope until second order diffraction of spectral lines is visible; record diffraction angles for second order diffraction of same five lines.

11. Calculate wavelength of light for each angle measured; using grating equation.

12. Compare measured wavelengths to actual wavelengths given in Table 1; state possible sources of errors in your measurement.

TABLE 1. STRONG HELIUM SPECTRAL LINES

Color	Wavelength (nm)	Color	Wavelength (nm)
Violet	388.6	Blue-green	492.2
Violet	402.6	Green	504.8
Violet	438.8	Yellow	587.6
Deep blue	447.1	Red	667.8
Blue	471.3	Red	706.8

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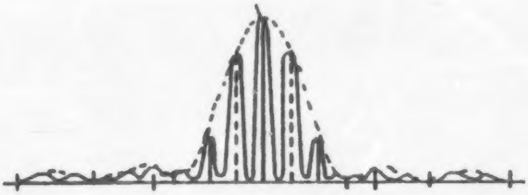
DATA TABLE				
Color	Order	Diffraction Angle°	Wavelength (nm) Experimental	Wavelength (nm) From Table
	1			
	2			
	1			
	2			
	1			
	2			
	1			
	2			
	1			
	2			

Grating spacing: d = _____ m.

SELF CHECK

1. In one or two sentences, summarize Huygens' principle.
2. Sketch wave pattern produced when plane waves are diffracted at an edge barrier.
3. Label sketch (below); include order of diffraction, single-slit diffraction envelope and double-slit diffraction peaks.



4. A diffraction grating has a spacing of 2×10^{-6} m. Calculate diffraction angles for the following:

   First order of 400 nm light.
   First order of 650 nm light.
   Second order of 550 nm light.

5. A diffraction grating produces fourth-order diffraction of 633 nm at 42°. What is the grating spacing?

6. For the above grating, what wavelength has third-order diffraction at 42°?

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Jenkins, Francis A. and White, Harvey E. Fundamentals of Optics. New York: McGraw-Hill Book Company, 1957.

Sears, F.W. and Zemansky, M.W. Modern College Physics, Part II: Fields, Waves, and Particles. Reading, MA: Addison-Wesley Publishing Company, Inc., 1956.

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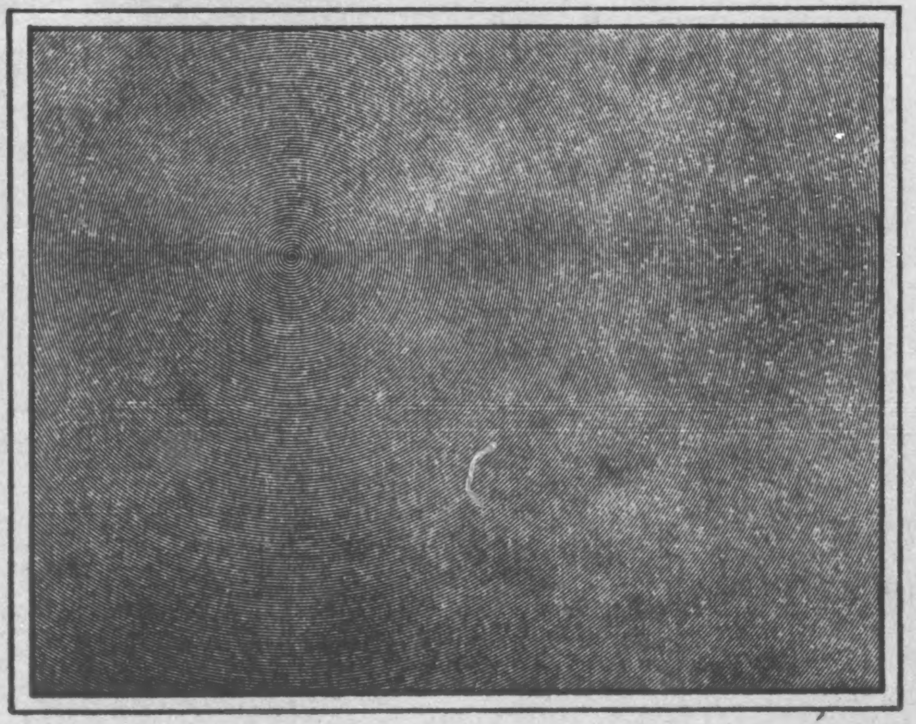
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 13
POLARIZATION - GLARE REDUCTION



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Electromagnetic radiation is made up of time-varying electric and magnetic fields moving through space. The polarization of light is a description of the orientation of its electric field in space. This module discusses characteristics of polarized light and methods of producing and measuring polarization of light. The origin of glare and its reduction by polarizing optical components is also presented. Polarization of laser light is measured in the laboratory.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13L4, "Lasers," and should be familiar with basic trigonometry.

OBJECTIVES

To complete this module, the student should be able to:

- Sketch the orientation of an electric field of unpolarized light, and of vertically and horizontally polarized light.
- Draw and label a diagram showing the orientation of an electric vector of light as it passes through a series of polarizers with transmission axes at specified angles.
- Calculate intensity of light transmitted by a polarizer, given the following:

  Maximum intensity transmitted when light is polarized parallel to transmission axis of polarizer.

  Angle between polarization direction and transmission axis of polarizer.
- Draw and label a diagram showing polarization by reflection.
- Explain in a short paragraph how polarized sunglasses reduce glare from horizontal surfaces.

- Given proper equipment, measure the transmission of a polizer/analyzer pair as a function of the angle between their transmission axes.

- Given proper equipment, measure Brewster's angle for a microscope slide in the laboratory.

DISCUSSION

Figure 1 shows an electromagnetic wave propagating through space. The electric field E, the magnetic field H and the direction of propagation x are all perpendicular to one another. Polarization of the electromagnetic wave describes the orientation of its electric vector in space. Thus, the wave in Figure 1 is plane polarized because 1) its electric field is always in one plane and 2) the plane does not change; that is, it is always vertical.

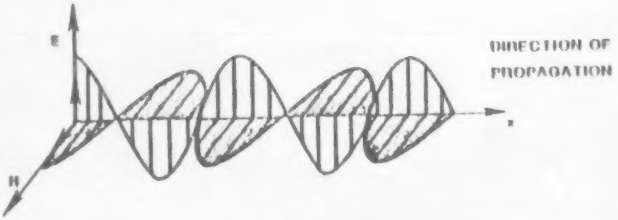
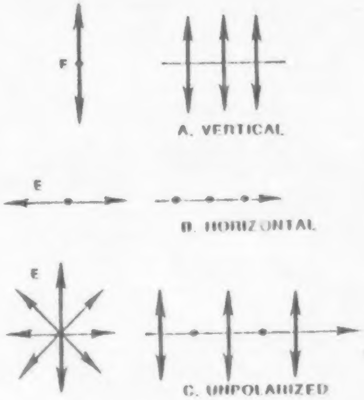


FIG. 1

There is no need to specify the direction of the magnetic field, because it always is perpendicular to both the electric field and the direction of propagation; magnetic field direction can be determined if these two facts are known.

Figure 2 shows three possible types of polarization and the symbol used to represent each in a diagram. In each case the figure on the right represents a side view and the figure on the left represents an end view of the ray of light. The electric field (Figure 2a) of the light is vertical (indicated by small vertical arrows on the light ray). Dots on the ray (Figure 2b) indicate horizonatal polarization; that is, it vibrates in and out of the page. Light that has random orientations of electric fields (Figure 2c) is called unpolarized light. This kind of light may be considered to be a combination of vertically and horizontally polarized components (indicated both by arrows and by dots).



A. VERTICAL

B. HORIZONTAL

C. UNPOLARIZED

FIG. 2

A polarizer is a device that transmits only light of a particular polarization. Only that light with its electric field oriented in the same plane as the polarization axis is transmitted.

In Figure 3, which shows unpolarized light striking a pair of polarizers, the first polarizer transmits the vertical component only. The second polarizer is oriented to transmit horizontally polarized light only; therefore, none of the vertically polarized light striking it is transmitted.

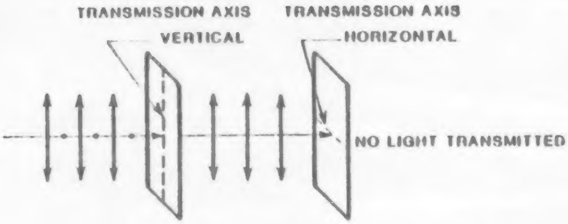

TRANSMISSION AXIS
VERTICAL
TRANSMISSION AXIS
HORIZONTAL
NO LIGHT TRANSMITTED

FIG. 3

In Figure 4, which shows polarized light striking a polarizer with its plane of polarization making an angle A with the transmission axis of the material, the electric field E of the incident light can be resolved into two vector components: the part parallel to polarization axis E_y is transmitted; the component perpendicular to axis E_x is not. The transmission (ratio of light intensity transmitted) of polarized light through a polarizing material is given by Equation 1.

$$T = \cos^2 A. \qquad (1)$$

where

T = Transmission.

A = Angle between plane of polarization of light and transmission axis of polarizer.

Example A shows how to use this equation in solving a problem.

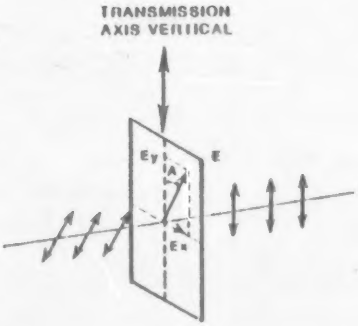

TRANSMISSION
AXIS VERTICAL
Ey
A
E
Ex

FIG. 4

EXAMPLE A: TRANSMISSION THROUGH A POLARIZER

Given: Vertically polarized light strikes a polarizer that can be rotated to any orientation.

Find: Transmission, with transmission axis of polarizer oriented:

a. Vertical.
b. At 45° to vertical.
c. Horizontal.

Solution: $T = \cos^2 A$

a. $T = \cos^2(0)$
$= (1)^2$
$T = 1.0$ (all light transmitted).

b. $T = \cos^2 (45°)$
$= (0.707)^2$
$T = 0.5$ (half of light transmitted).

c. $T = \cos^2 (90°)$
$T = 0$ (no light transmitted).

Figure 5 is a graph of transmission-versus-angle (between plane of polarization of light and axis of polarizer - angle A of Figure 4). As this curve indicates, transmission of a pair of polarizers can be controlled by rotating one of the polarizers. Some welding goggles incorporate a fixed polarizer and a second polarizer that may be rotated to adjust transmission.

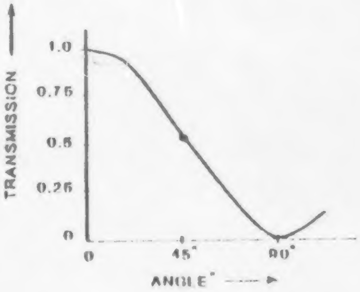


FIG. 5

Light may be polarized by several methods. The most familiar probably is polarization by absorption (Figure 6), which is used in polarizing sunglasses. The polarizer in Figure 6 consists of a plastic sheet containing needle-shaped crystals of herapathite (an iodine compound). These crystals absorb the horizontal components shown in the figure, but transmit most of the vertical components.

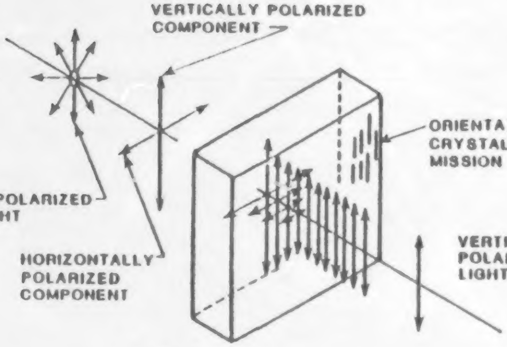

VERTICALLY POLARIZED COMPONENT
ORIENTATION OF CRYSTALS - TRANSMISSION AXIS
UNPOLARIZED LIGHT
HORIZONTALLY POLARIZED COMPONENT
VERTICALLY POLARIZED LIGHT

FIG. 6

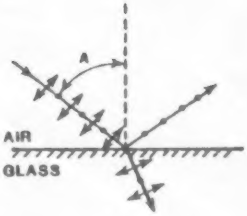


FIG. 7

Polarization by reflection of light from a surface is shown in Figure 7. Unpolarized light strikes surface with an angle of incidence A. A portion of the light is reflected, and the remainder is transmitted.

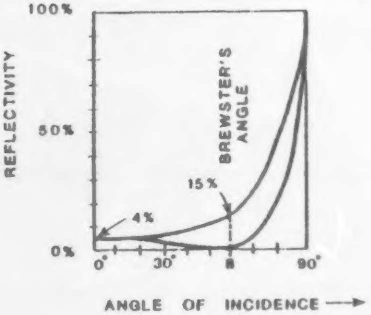


FIG. 8

The amount of each component (vertical and horizontal) reflected from the surface depends upon angle of incidence A (Figure 8). This graph indicates reflectivity of a glass surface as a function of 1) angle of incidence for light polarized in a plane perpendicular to surface ($\perp$) and 2) light polarized with its electric field parallel to the surface ($\parallel$). Perpendicular components always reflect more strongly, except in the case of normal incidence; thus, light reflected from most surfaces tends to be at least partially polarized.

Angle B (Figure 8), which is called Brewster's angle, is the angle of incidence for which none of the parallel component is reflected. In Figure 7, angle A is Brewster's angle; its reflected ray is horizontally polarized.

The transmitted ray contains all of the vertically polarized component and about 85 percent of the original horizontally polarized component.

Figure 9 shows a portion of a stacked-plate polarizer, which uses polarization by reflection to produce polarized light. Such a polarizer usually consists of four or more flat pieces of glass mounted at Brewster's angle. Reflected light is horizontally polarized, but the transmitted ray is not completely vertically polarized - it always contains some horizonatally polarized light not removed by reflection.

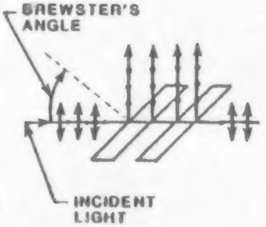


FIG. 9

Brewster's angle for a material may be calculated by using Equation 2:

$$B = \tan^{-1} n$$

or

$$n = \tan B \qquad (2)$$

where
B = Brewster's angle.
n = index of refraction.

Example B illustrates the usefulness of this equation in solving a problem.

EXAMPLE B: BREWSTER'S ANGLE

Given: Index of refraction of glass: $n = 1.6$.

Find: Brewster's angle.

Solution:

$$B = \tan^{-1} n$$
$$= \tan^{-1} (1.6)$$
$$B = 58°.$$

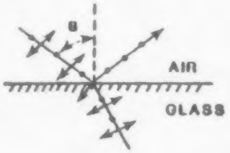


Figure 10 shows how the polarizing of sunglasses reduces glare. Most of the sunlight reflected from the surface of the water is horizontally polarized. Without the sunglasses this reflected glare is so bright that objects below the water surface cannot be seen. The lens material of the glasses absorbs all of the horizontal component and allows the vertical component to

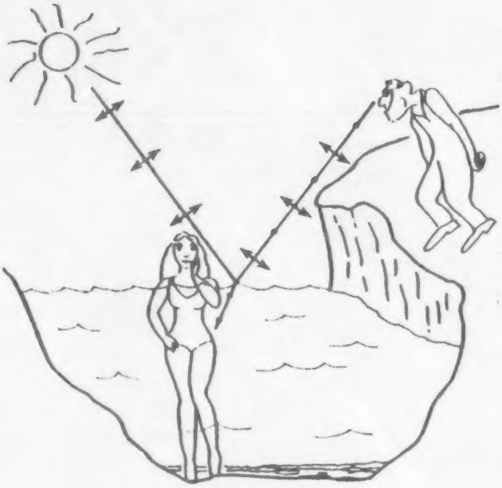


FIG. 10

pass through. The horizontally polarized glare is filtered out, and objects below the water surface are seen by vertically polarized light. This same principle applies to reflections from all horizontal surfaces.

The polarization axis of polarizing sunglasses is oriented vertically because most glare-producing surfaces (water, road surfaces, auto hoods and so on) are horizontal and produce horizontally polarized glare.

SUMMARY

Polarization refers to the orientation of the electric field of electromagnetic radiation in space. In unpolarized light, the electric field direction changes at random. In plane polarized light the electric field oscillates in a specific plane. Polarizers are optical components that transmit light of one polarization only. This transmission may be accomplished by reflecting light of other polarizations, as in a stacked-plate polarizer, or by absorbing unwanted light, as in the polarizing of sunglasses.

LABORATORY

TRANSMISSION OF A POLARIZER

MATERIALS

Low-power unpolarized helium-neon laser (2 mW or less).
Optical power meter.
Optical bench.
Two lens holders.
Three carriages.
Two linear polarizers with axis of polarization indicated.
Lab jack.

PROCEDURE

1. Set up equipment as shown in Figure 11.

2. Turn laser on; observe all safety precautions.

3. Rotate polarizer nearest laser so that its 0-180° (transmission) axis is vertical; this position yields vertically polarized light.

4. Rotate transmission axis of second polarizer to vertical.

5. Turn power meter on; carefully set dials to measure power of laser beam.

6. Make slight adjustments in orientation of second polarizer to achieve maximum transmission; record power in data table. If laser output power fluctuates, make all power readings at maximum point of needle swing.

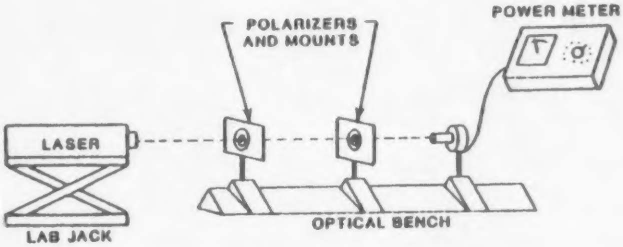


FIG. 11

7. Use pencil to make a small reference mark on polarizer mount just opposite zero degree mark on polarizer itself.

8. Rotate polarizer to bring 10° mark in line with reference mark.

9. Measure and record power.

10. Continue above process; take data every 10° until polarizer has been rotated 90°; change power meter scales as necessary; after each 90° make small adjustments to minimize transmission.

11. Calculate relative transmission (divide each power reading by the power at 0°).

12. Plot relative transmission-versus-angle on graph paper in data table.

13. Compare graph to that shown in Figure 5.

MEASURING BREWSTER'S ANGLE

MATERIALS

Low-power helium-neon laser.
Rotary table graduated in degrees, with stand.
Optical bench.
Two carriages.
Lens holder.
Polarizer.
Microscope slide.
Beeswax.
Index card.
Lab jack.

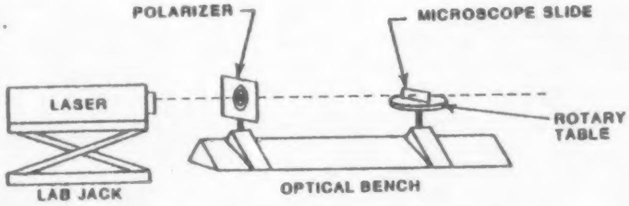


FIG. 12

PROCEDURE

1. Set up equipment as shown in Figure 12. Microscope slide is held in place by beeswax.

2. Turn laser on; observe all safety precautions.

3. Orient transmission axis of polarizer horizontally to produce horizontally polarized light - that is, vibrating in a plane paralled to top of rotary table.

4. Orient microscope slide to reflect laser bean back into laser output aperture; read and record angle on rotary table.

5. Slowly rotate table (with microscope slide) to position shown in Figure 13; observe reflected spot on index card.

6. Turn table to minimize intensity of reflected spot.

7. Measure and record new angular setting of rotary table.

8. Determine Brewster's angle (angle C in Figure 13); calculate index of refraction of slide (use Equation 2).

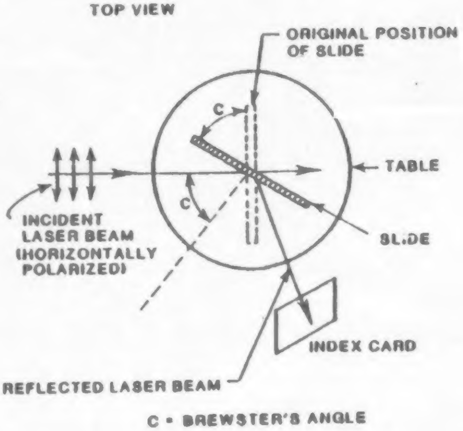
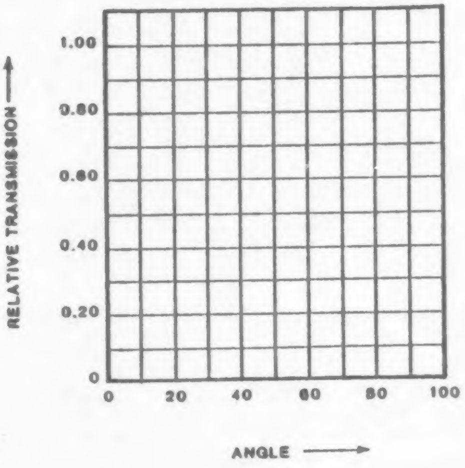

TOP VIEW
ORIGINAL POSITION OF SLIDE
C
C
TABLE
INCIDENT LASER BEAM (HORIZONTALLY POLARIZED)
SLIDE
INDEX CARD
REFLECTED LASER BEAM
C = BREWSTER'S ANGLE

FIG. 13



DATA TABLE		
Angle of Polarizer °	Power (mW)	Relative Transmission %
0		
10		
20		
30		
40		
50		
60		
70		
80		
90		

First angle measured: A = ______°.

Second angle measured: B = ______°.

Brewsters angle:

C = A - B = ______°.

Index of refraction: n = tan C

= tan (______°).

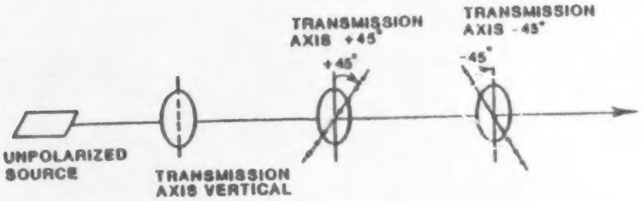
n = ______.

SELF CHECK

1. Sketch the electric fields of each of the following:

   Unpolarized light.
   Vertically polarized light.
   Horizontally polarized light.

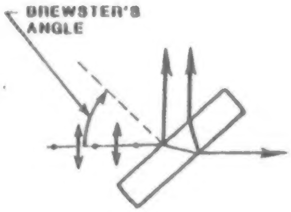
2. Indicate (on diagram) the polarization of light as it travels through an optical system:


TRANSMISSION AXIS +45°
+45°
TRANSMISSION AXIS -45°
-45°
UNPOLARIZED SOURCE
TRANSMISSION AXIS VERTICAL

3. If optical power through the first polarizer above is 10 mW, and there is no absorption and no reflection loss (perfect polarizer), calculate power transmitted by each of the other polarizers.

4. Unpolarized light strikes a piece of glass at Brewster's angle as shown on diagram (in the margin); indicate the polarization of 1) transmitted and 2) reflected rays.

5. Why is the axis of transmission vertical in polarized sun glasses?


BREWSTER'S ANGLE

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Jenkins, Francis A. and White, Harvey E. Fundamentals of Optics. New York: McGraw-Hill Book Company, 1957.

Technical Education Research Center - Southwest, ed. "Polarization." Module 5-8, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

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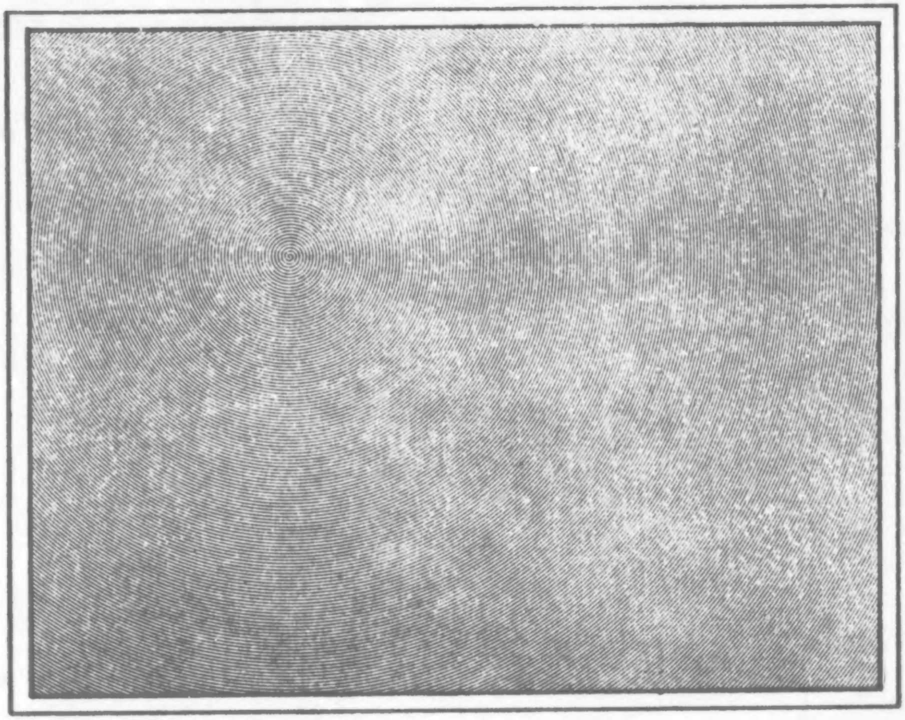
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 14

HOLOGRAPHY - THREE DIMENSIONAL PHOTOGRAPHY



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Ordinary photographs are two-dimensional images of three-dimensional scenes. Holography is a method of using coherent laser light to record and reproduce three-dimensional images. This module discusses the differences between holography and ordinary photography, as well as techniques used in making and viewing holographic images, along with several applications of holography. Holographic images will be reproduced and viewed in the laboratory.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," Application Module 13L4,"Lasers," and Application Module 13L12, "Diffraction Grating - Measuring the Wavelength of Light."

OBJECTIVES

To complete this module, the student should be able to:

- State in two or three sentences, differences between information recorded in an ordinary photograph and in a hologram.
- Draw and label a diagram of an equipment setup for producing a hologram.
- Sketch and describe setups for viewing real and virtual images of a hologram.
- List and explain, in two or three sentences each, three applications of holography.
- Given appropriate equipment, reconstruct real and virtual images of a hologram.

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PHOTOGRAPHY AND HOLOGRAPHY

In ordinary photography a lens is used to focus a real image of an object onto a light-sensitive film (Figure 1). This film records the relative amplitudes of light striking it and is processed to yield a two-dimensional image of the three-dimensional object. Ordinary photography records the amplitude (or light intensity) information from the scene but does not record phase information.

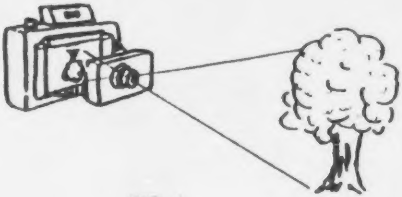


FIG. 1

Holography is a photographic process that reproduces a three-dimensional image of the object. Viewing a holographic image is much like looking through a window (Figure 2). The image in the hologram is three-dimensional and can be viewed from different angles to obtain different perspectives. The image of a high-quality hologram cannot be distinguished visually from the object itself. Holography records and reproduces both the amplitude and phase information of the original scene. It is the addition of this phase information that gives the holographic image a three-dimensional appearance.

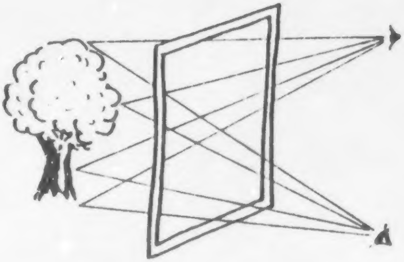
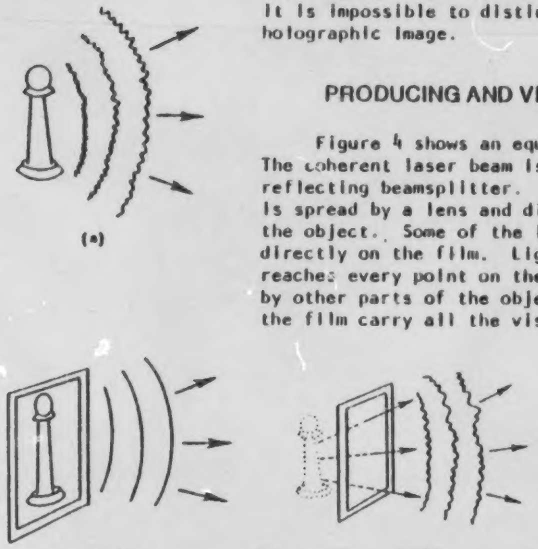


FIG. 2

Figure 3a shows the wavefronts of light reflected from an object. These complex wavefronts carry both phase and amplitude information to the eye. This information is received by the eye and processed in the brain to give the scene depth. In an ordinary photograph (Figure 3b) only the amplitude information is availablethus the scene is flat. A hologram (Figure 3c) provides an exact reproduction of the original light waves reflected from the object. Because these light waves carry all the information that the eye would have received from the scene itself, it is impossible to distinquish the real object from its holographic image.


(a)

(b)

(c)

FIG. 3

PRODUCING AND VIEWING HOLOGRAPHIC IMAGES

Figure 4 shows an equipment setup for making a hologram. The coherent laser beam is split into two beams by a partially reflecting beamsplitter. One of these, called the object beam, is spread by a lens and directed by a mirror to illuminate the object. Some of the light reflected from the object falls directly on the film. Light from each point on the object reaches every point on the film except where it is blocked by other parts of the object. The complex wavefronts reaching the film carry all the visual information about the object.

The reference beam, directed by another mirror, is spread to illuminate the film surface directly with spherical wavefronts. The light of the two beams interfere where they cross to produce a complex pattern of light and dark fringes. These fringes are recorded by the film.

When the processed hologram is viewed in ordinary light, no image is visible. The holographic image is reconstructed by illuminating the developed beam with a laser beam from the same direction as the original reference beam. When the reference beam strikes the film, the dark portions of the pattern on the film absorb some of the laser light while the clear portions allow more of the light to pass through. Light transmitted by the tiny clear areas is diffracted, thereby spreading as it leaves the hologram. Light from all illuminated areas of the hologram interferes to recreate the wavefronts that originally reached the film from the object. The result is that a three-dimensional image appears behind the film in the same position as the original object position (Figure 5).

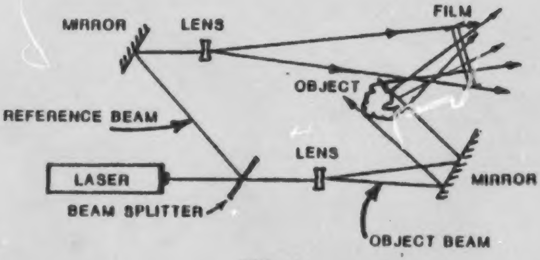


FIG. 4

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Figure 6 shows a hologram of a point source of light. The reconstruction beam in the figure strikes the film from the same direction as the original reference beam. The pattern of light and dark fringes acts as a diffraction grating. The images formed are actually first-order diffraction images from this grating. As with diffraction gratings, first-order diffraction occurs in the hologram on both sides of the undiffracted zero order (reconstruction beam direction) at equal angles (A at top of the hologram; B at bottom).

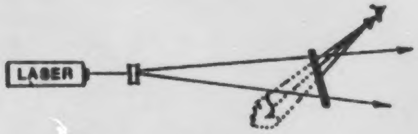

FIG. 5

One of the beams of light diverges and forms a virtual image of the original point source behind the film. The other converges and forms a real image at a point in front of the film. The virtual image may be viewed directly by the eye; the real image may be viewed by placing a white screen at its focal point.

If only a small area of the hologram is illuminated (as with a direct laser beam), the real image will be in good focus at any distance. Note that projecting the real image onto a screen destroys the phase information in the beam, resulting in a two-dimensional image.

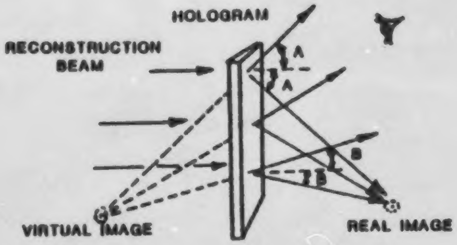

FIG. 6

Different perspectives may be achieved by illuminating different portions of the hologram. (Every part of the hologram contains information which will allow the entire image to be viewed.) The usual way of viewing a holographic image is to view the virtual image directly. If the hologram or the viewer's eye is not positioned properly, the real image may be seen instead. When viewed directly, this image is usually magnified and out of focus. If the real image is visible, the virtual image may be located by rotating the hologram 180° about an axis normal to its surface.

APPLICATIONS OF HOLOGRAPHY

Holograms are finding wide use in a variety of display applications. Because holographic images are true representation of an object, they are sometimes used to display expensive jewels or art objects. Other holographic displays are used in advertising and for decorative purposes.

In double exposure holography, one exposure of the hologram is made, the object is changed very slightly in some way and a second exposure is made without moving anything in the setup. This technique produces two almost identical holographic images on top of one another. At points where the light waves producing both images are in phase, the image is brighter; at points where they are out of phase, the image is dark.

An analysis of the light and dark areas of the image reveals the relative motion of various parts of the object between exposures. This kind of analysis is used in a process called holographic non-destructive testing. Figure 7 shows such a test on a radial tire. After the first exposure was made, the air pressure in the tire was increased slightly and a second exposure was made. Closely spaced fringes (shown by arrows) indicate 1) a large distortion with increasing air pressure, and 2) defects in the tire that could not be detected by any other means.

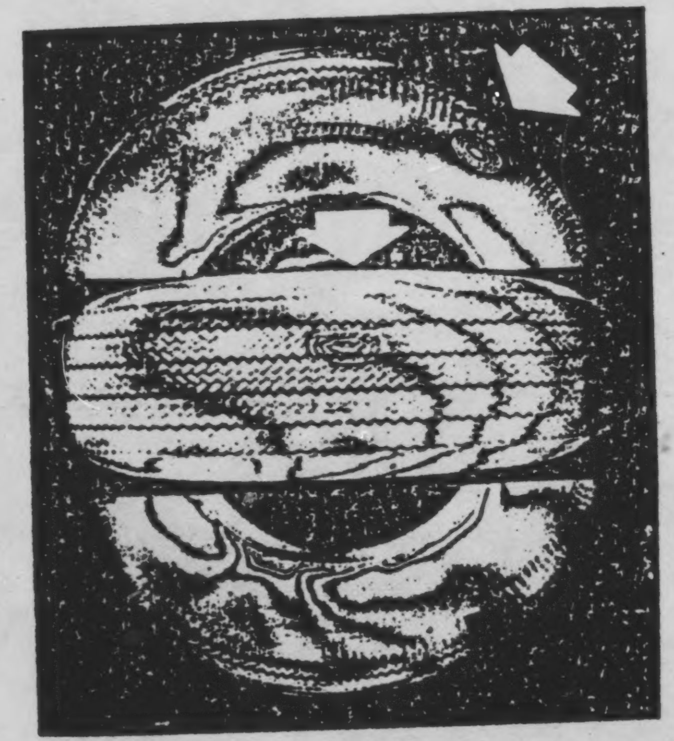

FIG.7

Holographic memories for computers can store large amounts of data in a small space. The data is stored in binary code as a matrix of points on the film that may or may not be exposed. The alternating clear and dark points produce a pattern in transmitted light that can be read by the computer. One

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commercial system can store 5.6 x 10^7 bits of information on a four-by four-inch holographic plate.

Holography is also a valuable research tool. A series of high-speed holograms may be taken of an object or event in the laboratory and examined in detail later. Information lost in ordinary photographs is retained in the holographic images. Holographic plasma diagnoses that use this technique are important in the study of controlled nuclear fusion.

SUMMARY

Holography is a technique that employees coherent laser light to produce three-dimensional photographic images. This accomplishment results from recording both the amplitude and phase information contained in the light reflected from an object. Reconstruction of the holographic image with another laser produces wavefronts of light that are identical to those originally reflected from the object. These diverging wavefronts produce the virtual image that appears as a three-dimensional image to the eye. A similar set of converging wavefronts produces a real image that can be projected on a screen but does not appear solid. Holography has applications in display, nondestructive testing and data storage.

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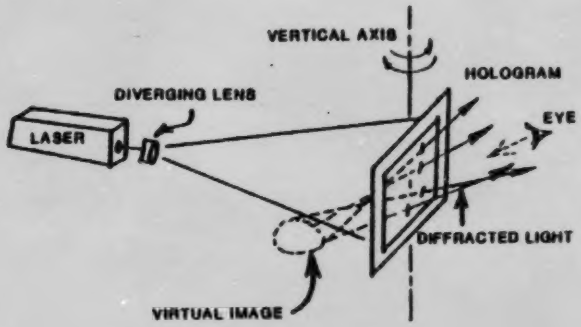
OBSERVING HOLOGRAPHIC IMAGES

MATERIALS

Low-power helium-neon laser (2 mW or less).
Short focal length diverging lens.
Transmission hologram.
Lens holder with base.
Small white screen, or 8" x 10" piece of white cardboard.

PROCEDURE

1. Set up equipment as shown in Figure 8.
2. Dim room lights.
3. Turn laser on; observe all laser safety precautions.
4. Align expanded beam to evenly illuminate hologram.
5. View hologram from distance of 12 to 18 inches at angle of about 30° to film normal; rotate hologram back and forth about vertical axis to obtain brightest image.



6. Rotate hologram about film normal; Observe real and virtual images. (Remember: Virtual image will be in focus; real image will not.) Describe virtual image quality and characteristics in data table.
7. Set up equipment as shown in Figure 9.
8. Move screen for convenient viewing of real image on screen.
9. Rotate hologram to produce sharpest and brightest real image on screen.

10. Move hologram so laser beam illuminates different areas on hologram; describe real image quality and characteristics in data table; include changes in image as different areas are illuminated.

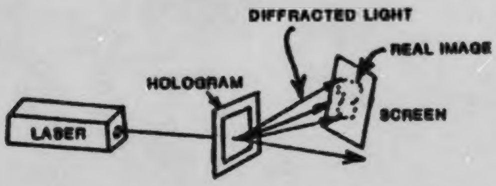

DIFFRACTED LIGHT
REAL IMAGE
HOLOGRAM
LASER
SCREEN

FIG. 9

DATA TABLE
Description of virtual image:
Description of real image:

SELF CHECK

1. What is the primary difference between information stored in an ordinary photograph and that stored in a hologram?
2. Draw and label a setup for producing a transmission hologram.
3. Draw setups for viewing the real and virtual images of a hologram.
4. List three applications of holography.

REFERENCES

Technical Education Research Center - Southwest, ed. "Holography." Module 5-9, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

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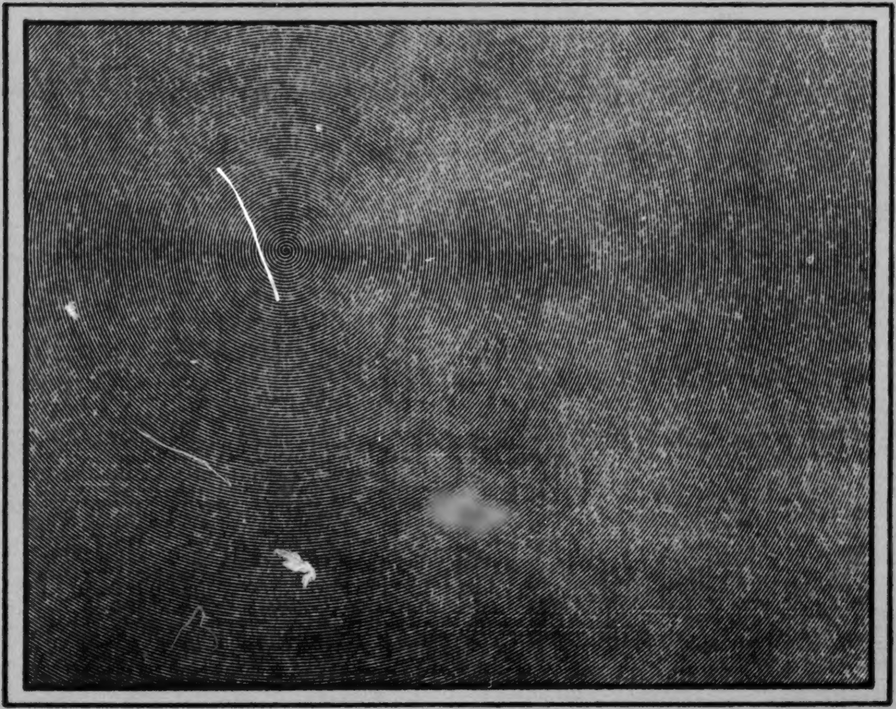
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 15

SPECTROSCOPY--
LIGHT ANALYSIS



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest

TERC - SW

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INTRODUCTION

One of the most important analytical methods available to modern science is a process called spectroscopy. It is an analysis of light emitted by, reflected from, or transmitted through a material, and it may be used to determine a variety of physical characteristics of the material. This module discusses several types of optical instruments used in spectroscopy and presents a wide variety of applications of spectroscopy in science and industry. In the laboratory the student will use a spectrophotometer to determine the transmission curve of a filter.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation," Application Module 13L2, "The Optical Spectrum," Application Module 13L6, "Optical Filters - Absorption of Light," Application Module 13L9, "Prisms - Refraction and Dispersion of Light," Application Module 13L11, "Interference - Testing Flat Surfaces," and Application Module 13L12, "Diffraction Grating - Measuring the Wavelength of Light."

OBJECTIVES

To complete this module, the student should be able to:

- Explain, in a brief paragraph, basic measurements performed in all types of spectroscopy.
- List three types of measurements that may be made by using spectroscopic techniques; give an application of each.
- Draw and label simple diagrams of following optical instruments:

  Spectrometer.
  Spectrograph.
  Monochromator.
  Spectrophotometer.

  Give an application of each.

- Explain, in a brief paragraph, how a spectrophotometer may be used to determine transmission of a sample for a particular wavelength of light.

- Given a spectrophotometer and a filter, draw transmission curve of filter for a wavelength (range of 350 nm to 700 nm).

TYPES OF SPECTOSCOPY

Spectroscopy is a process in which light of many wavelengths is dispersed to form a spectrum that may be observed or measured. In all types of spectroscopy the same two quantities must be determined: 1) wavelength of light present and 2) relative intensity at each wavelength. This information may be used to determine compositions and characteristics of materials producing, transmitting or reflecting the light.

Each type of atom or molecule has its own characteristic emission spectrum. The presence of a particular sequence of spectral lines in light emitted by a source indicates the presence of a particular atomic or molecular species in the source. Relative intensities at different wavelengths can reveal 1) relative amounts of each substance present and 2) source temperature. Study of emission spectra can lead to a determination of the composition of stars, flames and other light sources.

Each atom and molecule is capable of absorbing light with the same wavelengths as those of the light it can emit. If white light is passed through a partially transparent material, some of the light is absorbed. An analysis of the remaining (transmitted) light will give an absorption spectrum of the material. This technique can be used to analyze any substance that transmits light. It is a valuable tool in chemistry, physics, criminal investigation and medicine.

The analysis of light reflected from an object is also sometimes desirable. This technique is often used to check the quality and characteristic of mirrors and beamsplitters. Also, the reflected light can be used to reveal those wavelengths that have been absorbed by the material on reflection, and so functions in the same way as transmitted light.

INSTRUMENTS USED IN SPECTROSCOPY

A spectroscope is a device containing a prism or diffraction grating for dispersing light; it allows direct viewing of the sprectrum produced. If the device incorporates a method of measuring the wavelength of light, it also may be called a spectrometer.

Figure 1 shows a prism spectrometer that is commonly used in physics instruction. Such devices, though used primarily in education, employ the same principles as research instruments.

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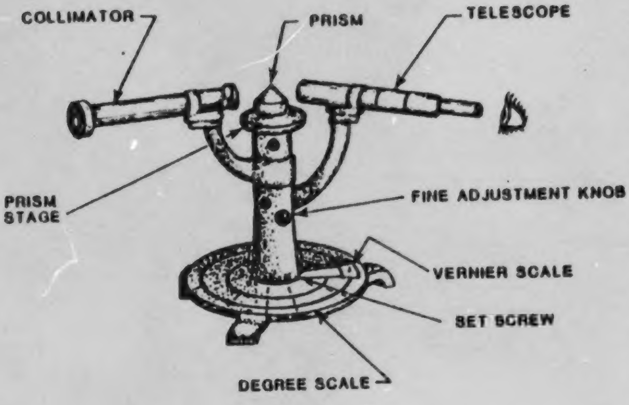

FIG. 1

Figure 2 shows a schematic of a grating spectrograph. This instrument is used to make a photographic record of the spectrum. Light enters through a narrow slit, is collimated by a concave mirror, then strikes a diffraction grating. The diffracted light is focused by a second concave mirror onto a photographic plate.

Figure 3 shows the emission spectra of several elements produced by this method. Each spectral "line" is an image of the entrance slit formed by a different wavelength present in the source light.

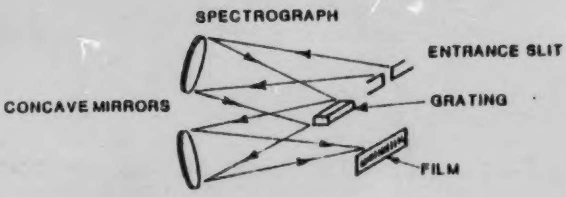

FIG. 2

Spectrographs, may be used in the study of absorption spectra; however, they are used primarily to identify and measure wavelengths of lines emitted from or absorbed by known atoms and molecules.

Figure 4 shows the optical components of a typical monochromator. This instrument is similar to a spectrograph but the photographic plate has been replaced with an exit slit. "White" light, containing a continuous disbution of wavelengths, is focused on the slit. Only a narrow range of wavelengths passes through the monochromator. The monochromatic wavelength emerging from the exit slit may be changed by rotating the grating. Monochromators are used in a variety of optical measurement systems to produce light of a specific desired wavelength; this process is used in measuring the absorption or reflection of materials. A monochromator, with one or more photomulipliers at its output slit, also is used in research to determine relative intensities of spectral lines.

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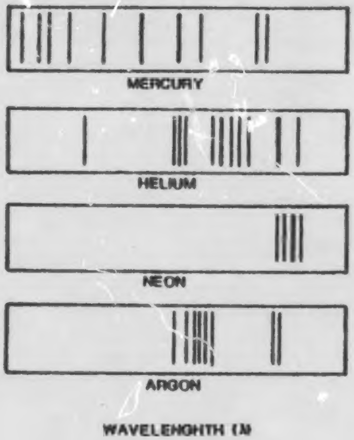
MERCURY
HELIUM
NEON
ARGON
WAVELENGHTH (Å)

FIG. 3

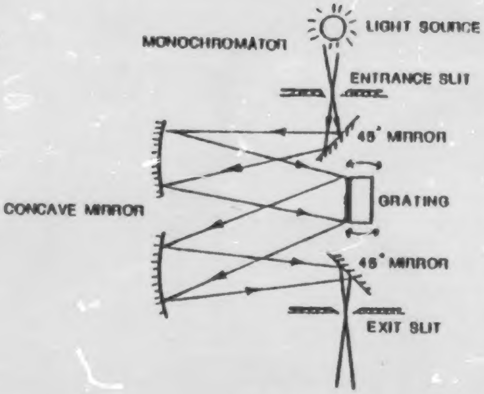
MONOCHROMATOR
LIGHT SOURCE
ENTRANCE SLIT
45° MIRROR
CONCAVE MIRROR
GRATING
45° MIRROR
EXIT SLIT

FIG. 4

Figure 5, a schematic diagram of a device called a spectrophotometer, shows that it consists of a white light source, a monochromator, a holder (or cell) for a sample of material to be analyzed, a photodetector and a display device. Such spectrophotometers are widely used as analytical instruments in chemical laboratories. They also are used widely to measure reflectance and transmission of optical components. The more sophisticated instruments split the beam from the monochromator into two parts. One part goes directly to a detector while the other passes through the

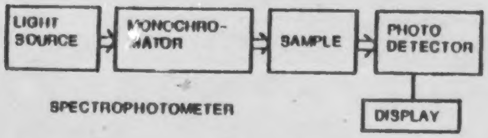
LIGHT SOURCE
MONOCHROMATOR
SAMPLE
PHOTO DETECTOR
DISPLAY
SPECTROPHOTOMETER

FIG. 5

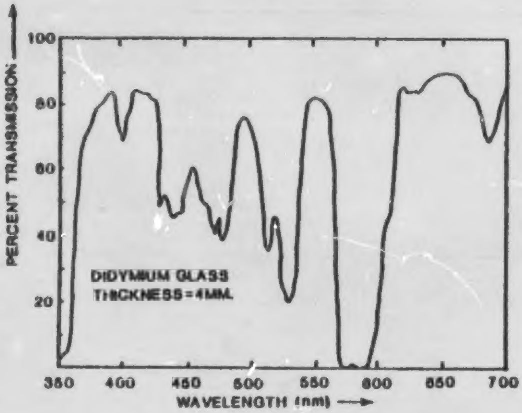

FIG. 6

sample to a detector. The two signal intensities are compared electronically and a permanent record of "transmission-versus-wavelength" is produced. Figure 6 shows a transmission curve for a piece of didymium filter glass, 4 mm thick, produced in this manner.

Figure 7 shows a small, inexpensive spectrophotometer, sometimes called a colorimeter, commonly used in analytical laboratories. Figure 8 shows the optical components of this instrument. With no curvette in the sample holder, the exit slit is blocked by a shutter; thus, no light reaches the phototube, which allows the amplifier to be set at zero transmission with the amplifier control.

The wavelength control is used to select the wavelength of light allowed to pass through the exit slit of the monochromator section of the device. With reference curvette containing a clear liquid placed in the sample holder, the light control is adjusted to give a reading of 100 percent on the meter. The curvette is then replaced by an identical one containing the solution to be analyzed; the transmission is read from the meter.

The wavelength is changed and the process is continued until there are enough data points to plot a curve. To identify the unknown solution, this curve then may be compared with similar curves for known substances. The concentrations of dissolved substances also may be determined from this data.

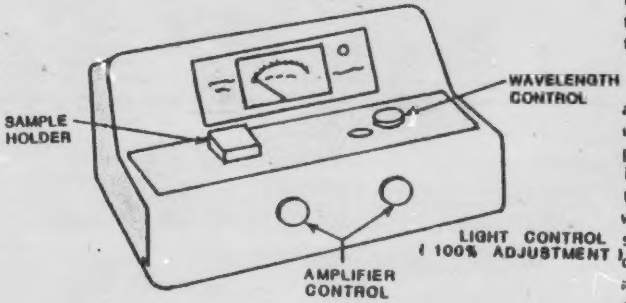

FIG. 7

(Note: An instrument of this type is used in the laboratory potion of this module.)

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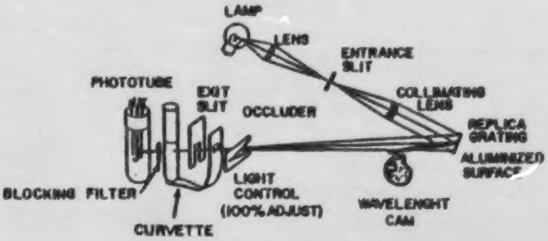
SUMMARY

When light is emitted by, reflected from or transmitted through a material, the resulting wavelength distribution of the light energy carries information about the material. Spectroscopy is the name for a related group of optical measurement techniques that provide information about a material through analysis of the light with which it interacts. The two basic quantities determined in all types of spectroscopy are 1) the wavelengths of light present and 2) their relative intensities. Optical instruments used in these determinations include spectrometers, spectrographs, monochromators and spectrophotometers.


LAMP
LENS
ENTRANCE SLIT
COLLIMATING LENS
REPLICA GRATING
ALUMINIZED SURFACE
PHOTOTUBE
EXIT SLIT
OCCLUDER
BLOCKING FILTER
LIGHT CONTROL (100% ADJUST)
WAVELENGHT CAM
CURVETTE

TRANSMISSION MEASUREMENT WITH A SPECTROPHOMETER

MATERIALS

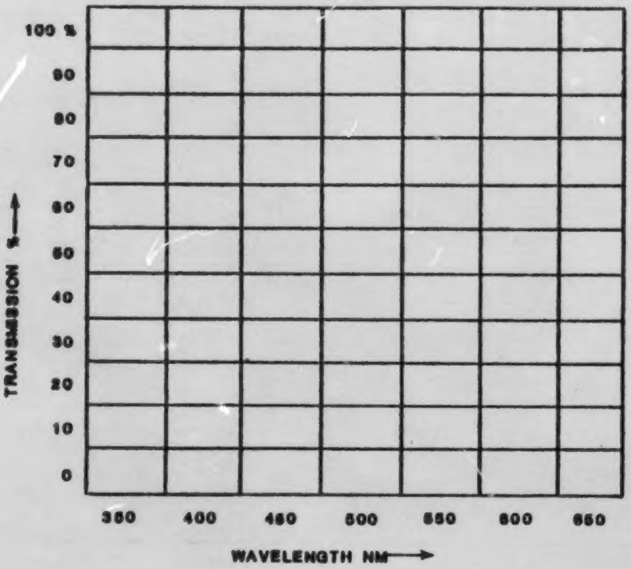
Spectrophotometer (Bausch and Lomb Spectronic 20, or equivalent).
Didymium filter (Sargent Welch #S-75416-90).
Filter adaptor.
Curvette.
Distilled water.

PROCEDURE

1. Install filter adaptor in spectrophotometer.
2. Plug in and turn on spectrophotometer; adjust amplifier control knob (left front) until meter needle indicates 0% T; allow spectrophotometer to warm up for 15 minutes before adjusting.
3. Fill curvette to half full with distilled water.
4. Set wavelength control knob to 350 nm; re-zero needle if necessary.
5. Insert curvette filled with distilled water into filter adaptor.
6. Adjust light control (right front) for a meter reading of 100% transmission.
7. Insert didymium filter; read % transmission; record reading in data table.
8. Remove curvette and filter; set wavelength control to 375 nm; re-zero needle if necessary.
9. Repeat steps 5 through 7 for this wavelength.
10. Continue this procedure, increasing wavelength by about 25 nm each time; include measurements of minima and maxima and their wavelengths.
11. Draw a curve of "transmission-versus-wavelength" on the graph provided.

12. Compare your graph to Figure 6; explain differences, if any, in the two graphs.

DATA TABLE			
Wavelength (nm)	Transmission (%)	Wavelength (nm)	Transmission (%)



GRAPH: TRANSMISSION VS. WAVELENGTH

SELF CHECK

1. What two quantities must be determined in all types of spectroscopy?

2. Give an application of spectroscopic analysis for each of the following:

   a. Light emitted by a source.
   b. Light transmitted through a material.
   c. Light reflected from a surface.

3. Identify an optical instrument that has each of the following characteristics:

   a. Light of many wavelengths is diffracted by a grating onto a photographic film to make a permanent record of the spectrum.

b. Light of many wavelengths is diffracted by a grating or refracted by a prism to fall on a slit; light of only one color passes through the slit.

c. Light of many wavelengths is refracted by a prism; the resulting spectrum is viewed directly.

d. Light of a single wavelength passes through a material; the transmitted intensity is measured.

4. Identify the optical instrument used in each of the following applications:

   a. To display a visible sprectrum for viewing by physics students.

   b. To make a permanent record of an emission spectrum from a gas discharge for accurate wavelength determination.

   c. To obtain a light of a single wavelength for photocell calibration.

   d. To measure transmission of an unknown solution for chemical analysis.

5. List steps necessary for measuring (with a direct reading spectrophotometer) transmission of a filter at a particular wavelength.

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Technical Education Research Center - SW, ed. "Spectrophotometers." Module 10-3, Laser/Electro-Optics Series, Waco, TX: TERC-SW, 1976.

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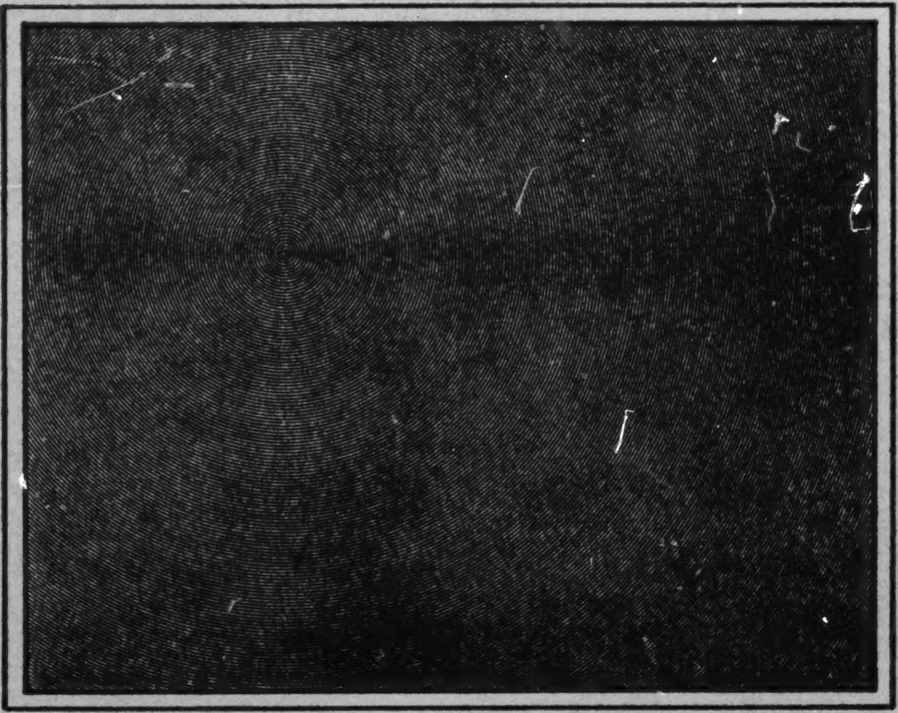
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 16

INFRARED RADIATION THERMOMETERS



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Many situations exist in which the temperature of objects must be measured, but conventional thermometers are not suitable for making the measurement. Examples include cases in which the environment around the object is extremely hostile (e.g., temperatures high enough to melt the conventional thermometer, extremely corrosive conditions, or very high pressures). For these cases and many others, infrared radiation thermometers provide a fast, accurate, and reliable method of measuring temperature without exposing the thermometer to the rigors of the object's environment.

In this module, the student will learn how the infrared radiation emitted from most objects can be used to determine the object's temperature. The design and limitations of a simple infrared radiation thermometer will be presented. In the laboratory, the student will make practical measurements with an infrared radiation thermometer.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13L2, "The Optical Spectrum."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

    Blackbody.
    Emissivity.
    Pyrometer.
    Thermogram.
    Passband.
    Absolute zero.

- Given two of these three quantities, find the third:

Total emitted power per unit area E.
Emissivity ε.
Absolute temperature T.

- Draw a block diagram of a simple infrared radiation thermometer, indicating the major optical and electronic components. Explain the purpose of each.

- Briefly describe three factors that limit the performance of infrared radiation thermometers.

- Given two of the following three quantities, find the third:

Emissivity ε.
Apparent temperature T_A.
Actual temperature T.

- Given the appropriate equipment, use an infrared radiation thermometer (1) to measure the temperature of ordinary objects; (2) to measure the apparent temperature of a window; and (3) to calculate a window's thermal resistance from these measurements.

When an object becomes hot enough it begins to glow due to energy, in the form of electromagnetic radiation, streaming away from the object. That portion of the radiation having wavelengths in the so-called "visible range" is detected by the eye as a distinctly colored glow. There is, however, extensive radiation with wavelengths outside the visible range leaving the object — particularly in the longer wavelength infrared region of the spectrum. In fact, for most objects, ranging in temperature from very cold to "white hot," infrared radiation constitutes, by far, the largest part of the object's total radiation output.

In general, any object that exists at a temperature above absolute zero emits electromagnetic radiation from its surface. Absolute zero is defined as the lowest possible temperature attainable and corresponds to -273.16°C. On the absolute or Kelvin temperature scale, absolute zero is assigned the value 0° Kelvin (K). The conversion between absolute and celsius temperatures is accomplished with the relation given by Equation 1.

$$T_K = T_C + 273.16 \tag{1}$$

where

T_K = absolute temperature.
T_C = celsius temperature.

BLACKBODIES

The simplest radiative behavior is exhibited by objects called "blackbodies." A blackbody is any object that absorbs all electromagnetic radiation incident upon it. The total power radiated per unit area of surface of a blackbody depends only upon the blackbody's temperature, as indicated by Equation 2.

$$E = \sigma T^4 \tag{2}$$

where

E = total radiated power per unit area.
T = absolute temperature of the blackbody.
σ = constant.

If E has units of watts per square meter (W/m^2) and T is in degrees Kelvin, then $\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$.

Equation 2 is employed in the solution of a problem in Example A.

EXAMPLE A: RADIATION OUTPUT OF A BLACKBODY

Given: A blackbody has an absolute temperature of 400 K.

Find: The total power radiated per unit area.

Solution: $E = \sigma T^4$ (Equation 2)

$$= 5.67 \times 10^{-8}\ \mathrm{W/m^2\ K^4} \times (400\ \mathrm{K})^4$$

$$E = 1.45 \times 10^3\ \mathrm{W/m^2}$$

The blackbody radiates 1.45 kW from each square meter of its surface.

Figure 1 is a graph of the radiated power per unit area (also called the "irradiance") of a blackbody at some temperature T plotted against the frequency of light radiated. Any other blackbody at the same temperature, no matter what it is made of, would be characterized by an identical graph.

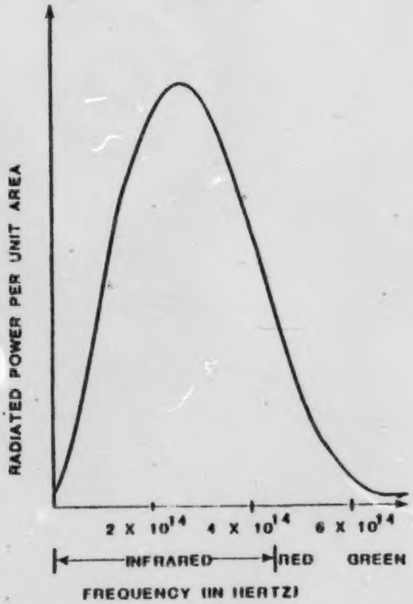


FIG. 1

Figure 2 depicts the irradiance-vs-frequency graphs for two blackbodies at different temperatures. Two features are readily apparent. The hotter blackbody gives off more radiation at all frequencies (including the infrared) than does the cooler. In addition, the peak in the curve occurs at a higher frequency (smaller wavelength) for the hotter blackbody than for the cooler. These facts hold true in general, so that whenever the temperature of a blackbody is increased, the irradiance at every frequency (and particularly in the infrared range) also increases; and the peak of the curve moves to a higher frequency.

EMISSIVITY

In practice, few objects behave like blackbodies. The surfaces of most objects reflect at least a small fraction of the radiation incident upon them; hence, ideal blackbodies rarely are encountered. The extent to which a real object radiates like a blackbody is expressed through a dimensionless parameter called the "emissivity," defined as "the fraction of an incident beam of radiation that would be absorbed by the surface." Thus, the emissivity of an ideal blackbody is 1, since all incident radiation would be absorbed. Similarly, the emissivity of a perfect reflector is zero, since all incident radiation would be reflected (none absorbed). The emissivities of real-world objects, then, must lie in the range from 0 to 1.

Because real objects absorb less light than blackbodies, they also radiate less. The total irradiance from a real object is given by Equation 3.

$$E = \epsilon \sigma T^4 \qquad (3)$$

where

E = total irradiance.
T = absolute temperature.
ϵ = the emissivity of the object's surface.
σ = constant (defined in Equation 1).

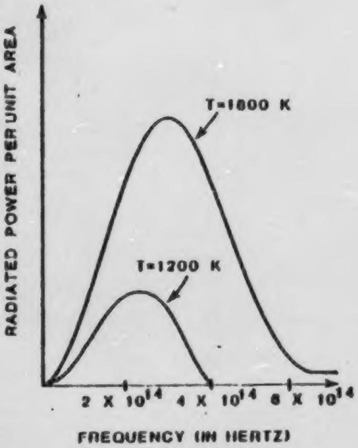


FIG. 2

Example B consists of a problem and its solution from Equation 3.

EXAMPLE B: EMISSIVITY OF AN OBJECT

Given: An object at a temperature of 500 K radiates energy at the rate of 2.13×10^3 W/m^2.

Find: Its emissivity.

Solution: $E = \epsilon \sigma T^4$ (Equation 3)

$$\epsilon = \frac{E}{\sigma T^4}$$

$$= \frac{2.13 \times 10^3 \text{ W/m}^2}{(5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)(500 \text{ K})^4}$$

$$\epsilon = 0.60$$

The emissivity of the object's surface is 0.60.

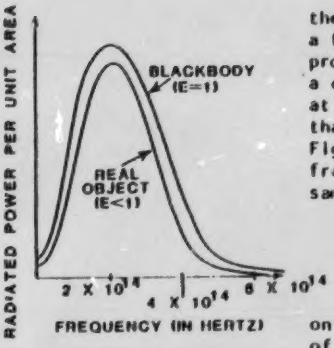


FIG. 3

A comparison of Equations 2 and 3 reveals that the total irradiance from a real object is less (by a factor equal to the emissivity) than the irradiance produced by a blackbody at the same temperature. As a consequence of this, the amount of radiation emitted at any frequency from the real object is less than that emitted by a blackbody at the same temperature. Figure 3 is a graph of the irradiance plotted against frequency for a blackbody and a real object at the same temperature.

INFRARED RADIATION THERMOMETERS

Because the radiation output of any object depends only upon the object's temperature and the emissivity of its surface, the temperature can be determined from measurements of the irradiance within a given range of frequencies. Any device that measures the radiation from a body in order to determine its temperature is called a "radiation thermometer," or "pyrometer." Since the majority of the radiation emitted by most objects is in the infrared range, many pyrometers are constructed to detect radiation in this range.

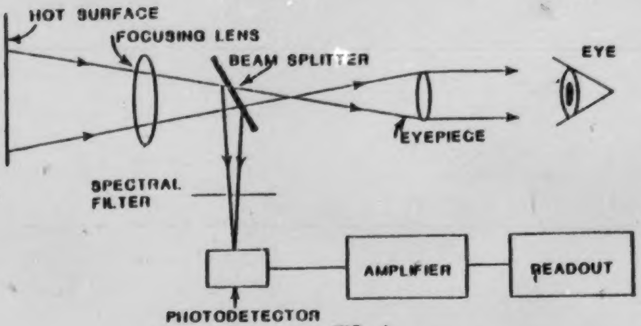


FIG. 4

A block diagram of the optical and electronic systems of a simple infrared radiation thermometer is shown in Figure 4. The optical system consists of a quartz focusing lens, a beam splitter, an eyepiece, and a spectral filter. The electronic system contains a photodetector, an amplifier, and a readout. The focusing lens admits radiation into the pyrometer and focuses it ultimately on the photodetector. The lens often is made of quartz because this material absorbs very little of the infrared radiation passing through it.

The beam splitter is a partially-silvered mirror that intercepts the beam after its passage through the focusing lens. The beam splitter reflects a known fraction of the incident radiation toward the filter and photodetector and transmits the remainder to the eyepiece.

The eyepiece is a lens that focuses the visible radiation in the transmitted beam for easy viewing by the human eye. This focusing capacity simplifies the process of aiming the pyrometer at the target object. Cameras loaded with special infrared sensitive film can be attached to the eyepiece in order that a thermogram of the object can be made. Thermograms will be discussed in more detail later in this section.

The spectral filter serves to transmit only a narrow range of infrared frequencies in the incident beam to the photodetector. The range of transmitted frequencies defines the passband of the pyrometer. The narrower the passband, the greater will be the inherent accuracy of the measurement. An ideal spectral filter transmits all the radiation having wavelengths (or frequencies) within the passband and absorbs the remainder of the beam. Figure 5 shows a graph of percent transmission plotted against wavelength for ideal, and actual, spectral filters with passband from λ_1 to λ_2.

The photodetector is an energy transformer that converts the radiative energy of the incident radiation to electrical energy in the form of a voltage or current. Many different devices can be used as photodetectors, the major criterion being that the photodetector must be sensitive to radiation within the pyrometer's passband. Some devices suitable for use as photodetectors include thermocouples, resistance thermometers, and semiconductor photocells.

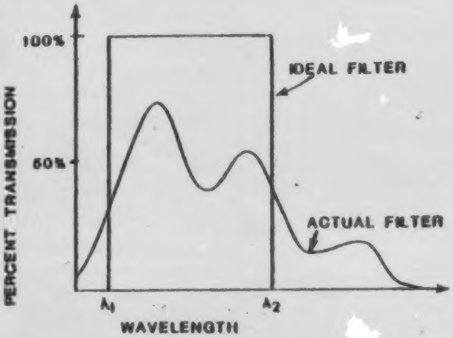


FIG. 5

The amplifier enhances the voltage or current produced by the photodetector. Amplification increases the magnitude of the output signal and allows easier measurements.

The readout is an instrument that measures the output from the amplifier. It may be as simple as an ammeter or voltmeter, whose output must be converted via calibration tables to temperatures.

PERFORMANCE FACTORS

In actual use, the performance of infrared pyrometers is limited by several factors, including the size of the area from which the pyrometer receives radiation, the distance from the pyrometer to the target, and the emissivity of the target surface.

The area of the target viewed by the pyrometer should be kept as small as possible. In this way, local temperature variations on the surface being measured will have less effect on the measurement. In addition, small viewing areas admit less stray radiation from sources other than the target. Such additional radiation would cause the temperature reading to be too high.

The distance between the target and the pyrometer should be minimized. Since the viewing area generally increases with increasing pyrometer-to-target distance, a small distance helps to ensure small viewing areas. Additionally, atmospheric gases absorb infrared radiation, so that the shorter the distance from the target to the pyrometer, the larger will be the amount of radiation reaching the detector.

Finally, the emissivity of the target surface can cause an error in the temperature measurement because the radiation from an object with emissivity less than one is less than that from a blackbody at the same temperature. Since most pyrometers are calibrated with respect to blackbodies, the temperature indicated (called the "apparent temperature") will be less than the actual temperature of the object. The actual and apparent temperatures are related through Equation 4.

$$T = \frac{T_A}{\sqrt[4]{\varepsilon}} \qquad (4)$$

where

T_A = apparent temperature (in K).
T = actual temperature (in K).
ε = emissivity.

The use of this equation is illustrated in Example C.

EXAMPLE C: ACTUAL TEMPERATURE OF A BODY

Given: Infrared radiation thermometer measurements on an object of emissivity $\varepsilon = 0.60$ indicate an apparent temperature of 700 K.

Find: Actual temperature of the object.

Solution:

$$T = \frac{T_A}{\sqrt[4]{\varepsilon}}$$

$$= \frac{700\ \text{K}}{\sqrt[4]{0.60}}$$

$$= \frac{700\ \text{K}}{0.88}$$

$$T = 795\ \text{K}\ .$$

The actual temperature is 795 K.

Many of the above limitations are overcome through the use of precision infrared radiation thermometers. These pyrometers make use of many clever, and often intricate, designs to extend their reliability. In particular, thermometers called "Blackbody Pyrometers" are designed to provide readings of the actual temperature of surfaces over a wide range of emissivities.

Another type of infrared radiation thermometer involves the use of thermograms. A thermogram of an object is a photographic or video image that records the infrared radiation leaving it. Variations in temperature are recorded as different colors or intensities in the image.

Although thermograms do not indicate the temperature of a surface as precisely as other pyrometers, they do record temperature variations extremely well. For this reason, they find extensive use in energy conservation because they indicate portions of structures that should have additional insulation. Thermograms also find increasing use in medical applications; for instance, tumors often are colder than surrounding healthy tissue and show up clearly on thermograms.

Infrared radiation thermometers of all types are employed in a variety of industrial applications in which the temperature of extremely hot or physically-inaccessible objects must be measured. These thermometers provide rapid, accurate measurements of temperature without being exposed to the harsh environments of the objects whose temperatures are being measured.

SUMMARY

Infrared radiation thermometers measure temperature over a wide range by detecting emitted infrared radiation. The instrument consists of an optical system that directs the radiation onto a photodetector and then to electronic systems that amplify and display the photodetector output. The performance of the pyrometer can be limited by its viewing area, distance from target, and target emissivity, although corrections can be made for these effects. Infrared radiation thermometers find wide usage in a variety of fields, including industry, medicine, and energy conservation.

APPARENT TEMPERATURE OF OBJECTS

MATERIALS

Infrared radiation thermometer.
Several heated objects such as those listed in Step 1.

PROCEDURE

1. Use the infrared radiation thermometer to measure the apparent temperature of several different familiar objects. Some suggested objects are an automobile engine (running), the polished metal surface of a hot toaster or oven, a piece of glowing metal.
2. Record the object, the pyrometer reading, and the corresponding apparent temperature of the object in the appropriate column of Data Table 1.
3. Explain the advantages of using the pyrometer rather than some other temperature-measurement devices.

ACTUAL TEMPERATURE AND APPARENT TEMPERATURE OF OBJECTS

MATERIALS

Infrared radiation thermometer.
Electric hot plate.
Three pieces of metal plate, each measuring approximately 2" x 2" x 1/8" — one of aluminum, one brass or copper, and one cast iron.

PROCEDURE

1. Lay metal squares flat on hot plate surface, closely grouping them near its center. Turn on hot plate, and adjust its

temperature setting to maximum. Allow sufficient time (30 min — 1 hr) for all three pieces to stabilize at the same temperature.

2. Record material of which each square is made and its emissivity in appropriate column of Data Table 2. (See References for source of emissivity data.)

3. Use pyrometer to measure apparent temperature of each square. Record the pyrometer reading and the apparent temperature for each. Be sure that the pyrometer receives radiation only from the sample whose temperature it is detecting.

4. Use the values of the emissivity and apparent temperature of each square in Equation 4 to calculate the actual temperature of each.

5. Discuss some applications of the infrared radiation thermometer.

THERMAL RESISTANCE OF A WINDOW

MATERIALS

Infrared radiation thermometer.
Mercury thermometer graduated in °C.
Meter stick or tape measure.
Window.

PROCEDURE

1. Use mercury thermometer to measure ambient temperature of air on each side of window. Record these temperatures in Data Table 3.

2. Measure and record length and width of glass portion of window. Calculate area of window.

3. From colder side of window, measure apparent temperature of window, using infrared radiation thermometer. Record pyrometer reading and corresponding apparent temperature in Data Table 3.

4. The total power radiated per unit area by window is given by Equation 3. Use Equations 3 and 4, along with apparent temperature of window, to calculate total power radiated per unit area.

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5. Calculate total power radiated by window.

6. Calculate temperature difference between opposite sides of window.

7. Using the following equation, calculate thermal resistance of window:

$$R = \frac{\Delta T}{P}$$

where

R = thermal resistance.
ΔT = temperature difference.
P = total power.

8. Describe how the insulation of a building might be tested and improved by such measurements and calculations.

DATA TABLE 1

Object	Pyrometer Reading	Apparent Temperature (in K)

DATA TABLE 2

Material	Emissivity	Pyrometer Reading	Apparent Temperature (in K)	Actual Temperature (in K)

DATA TABLE 3

Outside Temperature, T_O = __________ °C

Inside Temperature, T_I = __________ °C

Length, ℓ = __________ m

Width, w = __________ m   Area, $A = \ell w$ = __________ m^2

Pyrometer Reading = __________   Apparent Temperature, T_A = __________ K

Total Radiated Power per unit Area = $E = \varepsilon\sigma T^4$ (from Equation 3)

$$E = \varepsilon\sigma\left(\frac{T_A}{\sqrt[4]{\varepsilon}}\right)^4 \quad \text{(substituting from Equation 4)}$$

$$= \varepsilon\sigma\,\frac{T_A^{\,4}}{\varepsilon} \quad \text{(simplifying)}$$

$E = \sigma T_A^{\,4}$ = __________ W/m^2

Total Radiated Power , $P = EA$ = __________ W

Temperature Difference, $\Delta T = (T_O - T_I)$ = __________ °C

Thermal Resistance, $R = \frac{\Delta T}{P}$ = __________ °C/W

SELF CHECK

1. Define:

   Blackbody.
   Emissivity.
   Pyrometer.
   Thermogram.
   Passband.
   Absolute zero.

2. An object at a temperature of 550 K is characterized by an emissivity of 0.75. Find the following values:

   (a) The total power radiated per unit area by the object.
   (b) The apparent temperature that would be measured by an infrared pyrometer.

3. Draw a block diagram of a simple infrared radiation thermometer, showing the major optical and electronic components. Explain the purpose of each.

4. Briefly describe three factors that limit the performance of infrared radiation thermometers.

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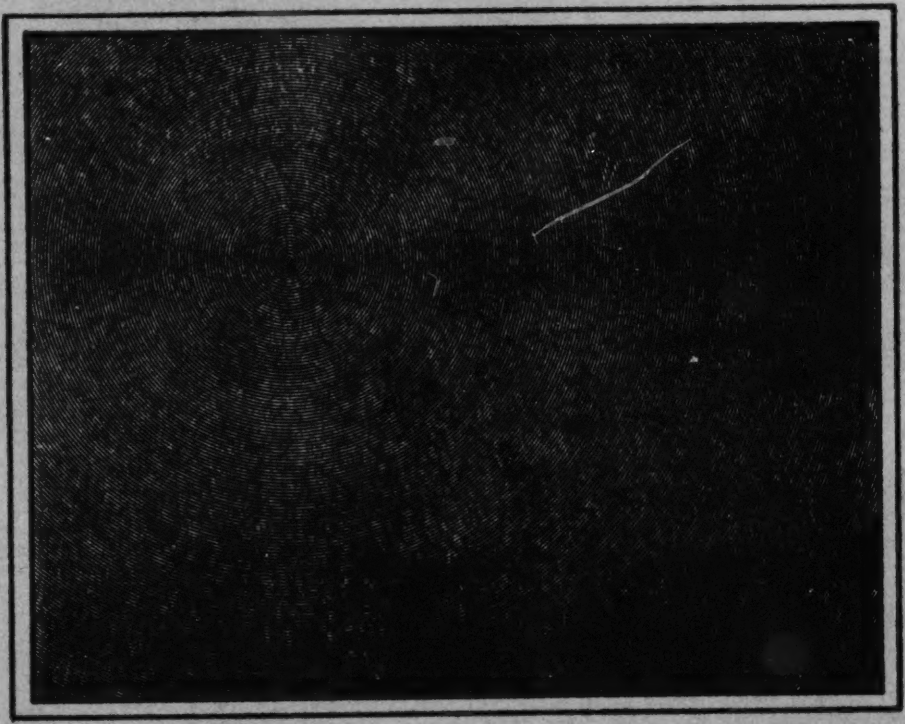
UNIFIED TECHNICAL CONCEPTS

MODULE 13 L 17

ILLUMINATION



LIGHT APPLICATION OF RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Probably the most commonly-encountered form of energy is radiant energy. In the form of heat and light, radiant energy plays an important role in every person's life.

This module discusses different quantities associated with the measure of radiant energy, especially of light in the visible range. The light output of various light sources is presented in terms of their efficiency and spectral composition. The minimum lighting requirements for various activities and the principles of operation and practical applications of light-measuring devices are presented. In the laboratory, the student will measure environmental light levels with a light meter and will determine their adequacy.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation"; and Application Modules 13L1, "Inverse Square Law – Spreading of Light," 13L2, "The Optical Spectrum," and 13L3, "Light Sources."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Give a brief definition (including the correct units) for the following quantities:

  Irradiance.
  Radiant intensity.
  Luminous flux.
  Illuminance.
  Luminous intensity.
  Luminous efficiency.

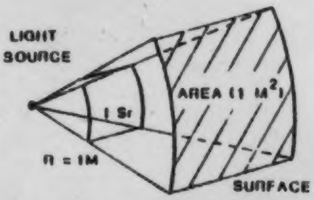
- Given two of the following three quantities, find the third: luminous flux, illuminance, and area (or luminous flux, luminous intensity, and solid angle).

- Given two of these three quantities, find the third: luminous flux, luminous efficiency, and input power.
- Describe, in a short paragraph, the operation, advantages, and disadvantages associated with incandescent and fluorescent sources.
- List the three objectives of a good lighting system.
- Determine the appropriate illuminance for different areas and the number of light sources necessary to provide it.
- Describe the operation of a color-corrected, photoelectric light meter.
- Given the appropriate equipment, measure room illuminance; and determine whether or not it is adequate for intended use.

DISCUSSION

Figure 1 illustrates a light source and a number of the more important quantities of illumination. The terms in Figure 1 are defined as follows:

- Luminous intensity (I) is a measure of the brightness of a light source. (The term "radiant intensity," used later in this module, refers to intensity in terms of power per unit solid angle.)
- Luminous flux (F) of source is the total amount of visible light energy produced by the source per second.
- Illuminance (E) of a surface is the amount of luminous flux per unit area that strikes it. Figure 1 shows luminous flux incident upon 1 m^2 of a spherical surface, 1 meter from the source.



LUMINOUS INTENSITY OF LIGHT SOURCE $= \frac{1\text{ LUMEN}}{\text{STERADIAN}}$ 1 CANDLELA

LUMINOUS FLUX F = 1 LUMEN

ILLUMINANCE OF SURFACE E $F/A = \frac{1\text{ LUM}}{M^2} = 1$ LUX

FIG. 1

- The symbol R is the distance from the source to the surface illuminated.

These quantities will be described in more detail in the following paragraphs.

IRRADIANCE AND RADIANT INTENSITY

Probably the most natural approach to quantifying the measurement of light involves the concepts of irradiance and radiant intensity. Light, after all, is a form of energy, and these two concepts make use of that fact. For a point source of light (not necessarily visible light) that radiates a total power P (energy per unit time) uniformly in all directions, the irradiance E at a distance R from the source is defined by Equation 1.

$$E = \frac{P}{4\pi R^2} \tag{1}$$

where

E = irradiance of a surface in watts/m^2 at distance R from a point source.
P = total power of point source in watts.
R = perpendicular distance from point source to surface in meters.

Radiant intensity of a point source radiating uniformly in all directions is given by Equation 2. (Note that radiant intensity is the power radiated per unit solid angle.)

$$I = \frac{P}{4\pi} \qquad (2)$$

where

I = radiant intensity.

4π = total solid angle in steradians surrounding a point source.

These quantities, however, for two reasons do not serve to measure the visual sensation of brightness. First, the eye is a very limited detector of radiant energy, and can sense only wavelengths between approximately 400 nm and 700 nm, the so-called "visible range." Energy radiated outside this range is not detected by the eye, and does not contribute, therefore, to the brightness of the source. For instance, a 40-watt fluorescent tube is brighter than a 40-watt incandescent bulb, because the bulb radiates much more energy as invisible infrared radiation than does the fluorescent tube.

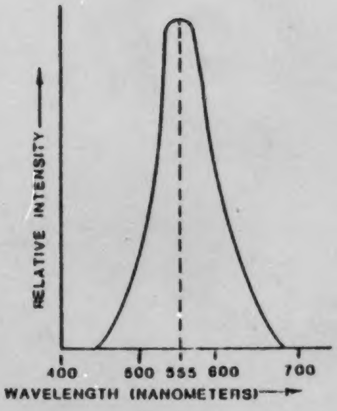


FIG. 2

Also important to the perception of brightness is the fact that even within the visible range, the eye is much more sensitive to some colors than to others. Figure 2 is a graph of the relative sensitivity of the human eye to the wavelengths of the visible spectrum. As can be seen from the figure, the eye is most sensitive to light of wavelength 555 nm; therefore, 1 watt of yellow light appears brighter than 1 watt of blue or red light.

LUMINOUS FLUX

Luminous flux is a quantity analogous to radiant power but compensated to include the previously-mentioned effects. In the International System of Units (SI), the unit of luminous flux is the lumen (lm) and is defined as that quantity of light power emitted within a solid angle of one steradian by 1/60 cm^2 of pure platinum at its freezing temperature. Luminous flux generally is assigned the symbol F.

ILLUMINANCE

A surface with luminous flux incident upon it is said to be "illuminated." The degree to which a surface is illuminated is measured by the quantity "illuminance," given by Equation 3.

$$E = \frac{F}{A} \qquad (3)$$

where

E = illuminance in lumens/m^2.
F = luminous flux incident on surface in lumens (lm).
A = area of surface in m^2.

In the SI system, illuminance is measured in "lux" (lx), where 1 lx = 1 lm/m^2. An alternate unit of illuminance is the "foot-candle" (fc), with a value of 1 fc = 1 lm/ft^2.

LUMINOUS INTENSITY

Luminous intensity is the property of a source emitting luminous flux, and is measured by the amount of luminous flux emitted per unit solid angle. This relationship between angle and flux is related by Equation 4.

$$I = \frac{F}{\omega} \qquad (4)$$

where

I = luminous intensity of a source in lumens/steradian (lm/sr).
ω = solid angle.

Notice that Equation 2, previously given, is a special case of Equation 4. The SI unit of luminous intensity is the candela (cd), with a value of 1 cd = 1 lm/sr.

Example A demonstrates the use of Equations 3 and 4 in solving a typical problem.

EXAMPLE A: LUMINOUS PROPERTIES OF A LIGHT BULB

Given: A 100-watt light bulb radiates uniformly with luminous intensity of 75 cd.

Find:

(a) The luminous flux produced by the bulb.
(b) The illuminance at the surface of a sphere of radius 2 m centered on the bulb. (Note: At a distance of 2 m from an ordinary light bulb, the bulb can be treated as a "point source" with little error.)

Solution: (a)

$$I = \frac{F}{\omega}$$

$$\therefore F = I\omega$$

Since light is emitted uniformly in all directions, $\omega = 4\pi$ sr (solid angle subtended by a sphere). Then:

$$F = (75 \text{ cd})(4\pi \text{ sr})$$

$$= 942 \text{ cd}\cdot\text{sr} = 942 \frac{\text{lm}}{\text{sr}} \cdot \text{sr}$$

$$F = 942 \text{ lm}$$

(b) $$E = \frac{F}{A} \quad (\text{where } A = 4\pi R^2 \text{ for a sphere})$$

$$= \frac{942 \text{ lm}}{4 \ (2\text{m})^2}$$

$$= 18.7 \text{ lm/m}^2$$

$$E = 18.7 \text{ lx}$$

LUMINOUS EFFICIENCY

One common problem that arises in connection with lighting systems is the determination of their relative efficiency. A quantity that describes the efficiency of a lighting device is called "luminous efficiency," stated by Equation 5.

$$L = \frac{F_{out}}{P_{in}} \qquad (5)$$

where

L = luminous efficiency.
F_{out} = luminous flux radiated in lumens.
P_{in} = input power in watts.

The SI unit of luminous efficiency is the lumen per watt (lm/W). The larger the luminous efficiency of a lighting device, the greater is the proportion of its input power converted to light. Examples B and C show the use of Equation 5 in determining luminous efficiency.

EXAMPLE B: LUMINOUS EFFICIENCY OF AN INCANDESCENT BULB

Given: A 40-watt light bulb produces a luminous flux of 500 lm. A 60-watt bulb produces 855 lm.

Find: The luminous efficiency of each bulb.

Solution: $L = \frac{F_{out}}{P_{in}}$

40-watt bulb: $L = \frac{500\ \text{lm}}{40\ \text{W}}$

$L = 12.50\ \text{lm/W}$

60-watt bulb: $L = \frac{855\ \text{lm}}{60\ \text{W}}$

$L = 14.25\ \text{lm/W}$

The 60-watt bulb has the greater luminous efficiency.

There are two basic types of lighting fixtures generally used for home, office, and industrial lighting; these types are the incandescent bulb and the fluorescent tube. The incandescent bulb consists of a tungsten filament supported inside a glass bulb. The bulb may be evacuated or filled with an inert gas. Electrical current flowing through the filament heats it to incandescence and causes it to glow. Figure 3 shows the relative intensity, graphed as a function of wavelength, of the light produced by a typical incandescent bulb. The cross-hatched region denotes the visible portion of the spectrum. The major cause of the inefficiency associated with incandescent lamps can be deduced from Figure 3. Only a small fraction of the radiation emitted is in the visible range; far more is radiated in the infrared and ultraviolet regions, and goes undetected by the eye. Thus, the low values for the luminous efficiency of incandescent lamps exists because they emit radiation over a range of wavelengths much wider than the visible range.

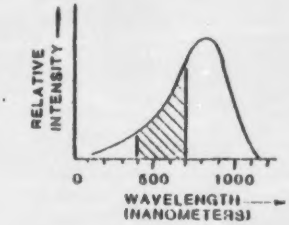


FIG. 3

A more efficient light source would compress the emitted wavelengths as closely as possible around the visible range. A device that accomplishes this is the fluorescent tube. This lamp is comprised of low-pressure mercury vapor confined within a glass tube. The mercury atoms are excited electrically into higher energy states, and emit photons of ultraviolet light when they return to their lowest energy state. These photons are absorbed by the atoms of a fluorescent material coated inside the glass tube. As a result, the atoms are raised to higher energy states. In returning to their ground state, however, the fluorescent atoms undergo a series of lower energy jumps. Hence, an atom excited by a single ultraviolet photon may emit two or three photons in the visible range as it returns to its original energy state (Figure 4).

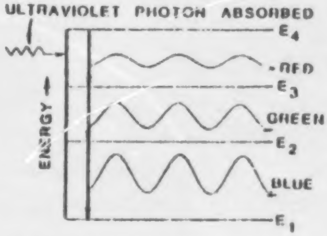


FIG. 4

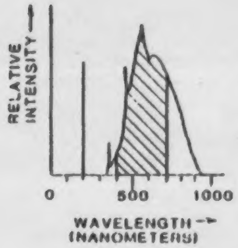


FIG. 5

When the tube has been coated with a suitable fluorescent material, most of the ultraviolet light produced by the mercury atoms can be re-emitted in a relatively-continuous range of wavelengths of visible light, as seen in Figure 5. Because most of the emitted radiation is in the visible range, the fluorescent tube provides more illumination than an incandescent lamp that consumes the same power.

Because of their high luminous efficiency, fluorescent lamps usually are chosen for large-scale lighting applications, both because they save operating costs (require less power to provide a given illuminance), and because they produce little heat to burden cooling plants. In addition, fluorescent tubes exhibit long operating lifetimes, seldom requiring replacement. The major drawbacks associated with fluorescent tubes is their relatively high cost of initial installation and replacement.

Incandescent bulbs, on the other hand, are much less efficient than fluorescent tubes, producing significant amounts of heat (infrared radiation). Their short lifetimes make relatively frequent replacement necessary, although installation and replacement costs are fairly low.

EXAMPLE C: LUMINOUS EFFICIENCY OF A FLUORESCENT TUBE

Given: A 40-watt incandescent bulb produces a luminous flux of 480 lm. A 40-watt fluorescent tube has a luminous efficiency five times greater than the bulb.

Find: Amount of luminous flux produced by the fluorescent tube.

Solution: The luminous efficiency of the bulb is as follows:

$$L_b = \frac{F_{out}}{P_{in}}$$

$$= \frac{480\ \text{lm}}{40\ \text{W}}$$

$$L_b = 12\ \text{lm/W}$$

The luminous efficiency of the fluorescent tube is then the following:

$$L_t = 5 \times L_b$$

$$= (5)(12\ \text{lm/W})$$

$$L_t = 60\ \text{lm/W}$$

The luminous flux produced by the tube now can be found from Equation 5:

$$L = \frac{F_{out}}{P_{in}}$$

$$F_{out} = L\,P_{in}$$

$$= \left(60\ \frac{lm}{W}\right)(40\ W)$$

$$F = 2400\ lm$$

The luminous flux produced by the fluorescent tube is 2400 lumens.

Example C indicates the degree to which the light output of incandescent and fluorescent lamps may differ.

ADEQUATE ILLUMINATION

In order to illuminate an area adequately, three goals must be achieved:

- Adequate illuminance must be provided.
- Sources of glare must be eliminated.
- Shadows must be eliminated.

The amount of illuminance required for a given area depends upon the kind of human visual activity performed there. In general, the tasks that are more demanding on a worker's eyesight require higher illuminance. Table 1 lists illuminance levels appropriate for different areas and activities.

TABLE 1. ADEQUATE ILLUMINANCE FOR DIFFERENT AREAS

Optimum Illuminance (fc)	Acceptable Range (fc)	Activity in Room
10	10 - 20	Conference Auditoriums Cafeterias Stockrooms Washrooms

20	15 - 35	Classrooms Filing Libraries Woodworking
50	35 - 70	Bookkeeping Stenographic General Merchandising Sewing Spray Painting
100	70 - 150	Drafting Show Windows Proofreading Machining

The elimination of glare also is an important factor in the design of a lighting system. Glare results from extremely bright light sources in the line of vision. Although most incandescent bulbs are frosted to reduce glare, they generally produce more glare than fluorescent tubes. Glare usually is reduced through the use of shades or translucent covers to block the light source from the line of sight. Lighting systems that reduce glare in this way are called "indirect," or "diffusive," lighting systems.

Shadows in the illuminated area can be reduced through the use of "extended" light sources; these sources usually consist of several lights at intervals throughout the area to be illuminated.

Example D shows how the principles presented thus far are applied in designing a simple lighting system.

EXAMPLE D: DESIGN OF A SIMPLE LIGHTING SYSTEMS

Given: A classroom having dimensions of 15 ft x 20 ft is to be illuminated with regularly-spaced, diffusive light sources. The light sources available are 40-watt, 480-lumen, incandescent bulbs or 40-watt, 2400-lumen fluorescent tubes. Assume that 50% of the luminous flux produced by either source is directed into the area to be illuminated.

Find: The number of sources necessary to illuminate the room adequately, using (a) only incandescent bulbs and (b) only fluorescent tubes.

Solution: From Table 1 the optimum illuminance for a classroom is 20 fc. The area to be illuminated is –

$$A = (15\ \text{ft})(20\ \text{ft}) = 300\ \text{ft}^2$$

The luminous flux necessary to provide this illuminance is found from Equation 3 as follows:

$$E = \frac{F}{A}$$

$$F = EA$$

$$F = 20\ \text{fc} \times 300\ \text{ft}^2 = 20\ \frac{\text{lm}}{\text{ft}^2} \times 300\ \text{ft}^2 = 6000\ \text{lm}$$

(a) Since only 50% of the luminous flux from each source is directed into the region to be illuminated, each incandescent bulb contributes (0.50)(480 lm) = 240 lm. Thus, the number N of bulbs required is found from –

$$N = \frac{F}{240\ \text{lm}}$$

$$= \frac{6000\ \text{lm}}{240\ \text{lm}}$$

$$N = 25$$

(b) Similarly each fluorescent tube contributes –

(0.50)(240 lm) = 1200 lm.

Therefore: $$N = \frac{F}{1200\ \text{lm}}$$

$$= \frac{6000\ \text{lm}}{1200\ \text{lm}}$$

$$N = 5$$

The area can be illuminated adequately with 25 incandescent bulbs or with 5 fluorescent tubes.

THE LIGHT METER

In practice, levels of illumination are measured with a light meter. Virtually all light meters used by lighting engineers and photographers to measure illuminance are of the photoelectric type. Light is admitted through an aperture into the light meter, where it strikes a photocell. The photocell converts the radiant energy of the photons into electrical energy in the form of an electric current. The magnitude of the current is proportional to the intensity of light. An ammeter on the device measures the current and is graduated to provide a readout in foot-candles or lux.

The basic problem associated with this device is that it responds to irradiance (power/area); whereas, the human eye responds to illuminance (luminous flux/area). Hence, the light meter gives identical readings when exposed to violet light or to yellow light, if the irradiance levels are equal, although the illuminance provided by the yellow light is much greater. (See Figure 1.)

This problem can be solved by use of a photometric filter between the light source and the light meter. The photometric filter selectively absorbs different amounts of the various colors of light comprising the visible range in such a way that the irradiance at the photocell is proportional to the illuminance at the surface of the filter. Use of the filter causes the light meter to exhibit a response similar to that of the human eye. Light meters with built-in photometric filters are said to be "color-corrected."

SUMMARY

Illuminance of a surface is equal to the luminous flux per unit area that strikes it. Illuminance and other important quantities associated with light radiation can be calculated and/or measured to provide the data from their proper use. Adequate illumination is important for a variety of human activities; however, a study of the efficiency of different light sources and the areas to be illuminated can result both in improved lighting and in energy conservation.

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DETERMINING ADEQUACY OF ILLUMINANCE

MATERIALS

Color-corrected photoelectric light meter with scale graduated from 0-75 fc (e.g. Sargent-Welch #3588 or equivalent).

PROCEDURE

1. Measure illuminance in at least five different rooms in your building. Record the room and/or activity being performed therein, along with measured illuminance, in Data Table. NOTE: If possible, choose a room or activity from each range of Table I. Indicate type of lighting (whether fluorescent or incandescent).
2. Use Table I to determine range of illuminance adequate for this room or activity. Record range in the data Table.
3. Make a note in the Data Table, indicating whether or not the measured illuminance falls within this range.
4. Discussion questions: (1) In the rooms tested, was there, on the average, not enough illuminance, or more than required? (2) How might such measurements as accomplished in this laboratory procedure be useful in conserving energy and money?

DATA TABLE

Room	Kind of Activity	Measured Illuminance	Bulb Type (fluorescent or incandescent)	Range (from Table I)	Check if Adequate and Comment
1					
2					
3					
4					
5					

SELF CHECK

1. Define and give units for the following terms:

    Irradiance.
    Radiant intensity.
    Luminous flux.
    Illuminance.
    Luminous intensity.
    Luminous efficiency.

2. A light source radiates light uniformly through a hemisphere of radius 50 cm. The luminous intensity of the source is 160 cd. Find the following:

    (a) Luminous flux radiated out of the hemisphere.
    (b) Illuminance at the surface of the hemisphere.

3. Determine which of these is more efficient:

    (a) A 100-watt bulb that radiates 1800 lumens.
    (b) A 75-watt bulb that radiates 1200 lumens.

4. Compare the operation and luminous efficiency of the incandescent bulb and the fluorescent tube.

5. List the three objectives of a good lighting system.

6. Determine the number of 60-watt, 3000 lm/W fluorescent tubes needed to provide adequate illuminance for a cafeteria of dimensions 15 m x 12 m.

7. Describe the operation of a color-corrected, photoelectric light meter.

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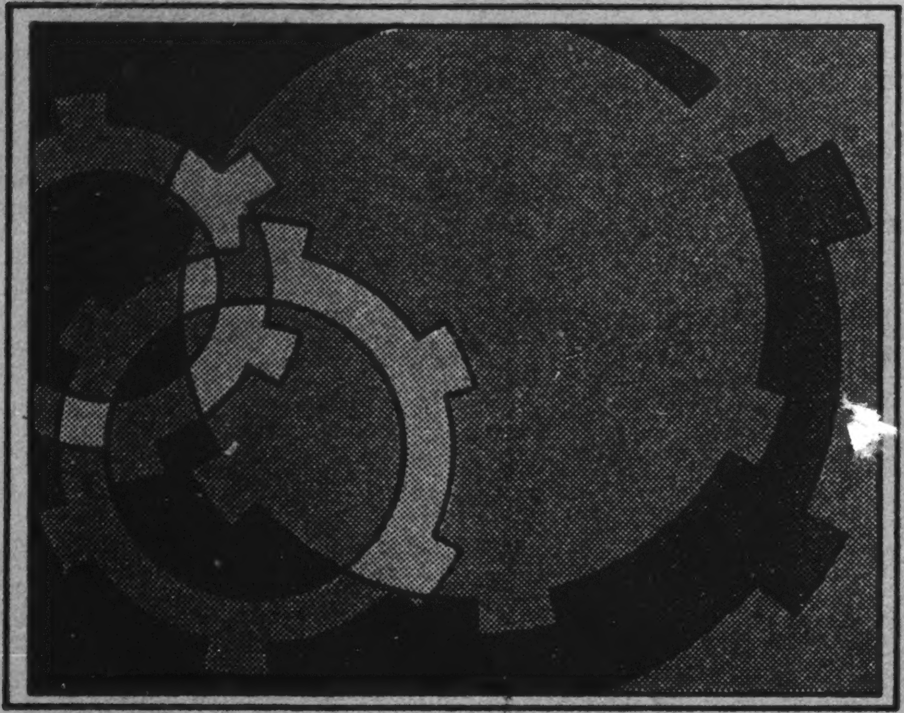
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 13L18

SINGLE LENS REFLEX CAMERA



LIGHT APPLICATION OF RADIATION

Technical Education Research Center-Southwest TERC-SW

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INTRODUCTION

THE SINGLE LENS REFLEX CAMERA

The camera is an optical device that records the pattern or image of objects that produce or reflect light. The camera is utilized to record scenes, portraits, data displayed on oscilloscope tubes, stages of manufacture (for later verification), and many other objects and processes. A single lens reflex camera (SLR) allows the photographer to view a scene, to focus, and to measure light intensity through the same lens used in taking photographs. This module introduces the optics, shutter speed, f-stop (lens opening), metering, film, viewing, and focusing of the SLR camera. In the laboratory, the student will determine image characteristics and depth of focus.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation"; and Application Modules 13L1, "Inverse Square Law — Spreading of Light," 13L9, "Prisms — Refraction and Dispersion of Light," and 13L10, "Lenses — Focusing and Spreading of Light."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Single lens reflex camera (SLR).
  Normal, telephoto, and wide-angle lenses.
  Shutter and shutter speed.
  Aperture.
  ASA number.
  Reflex viewing.

- Calculate the focal length of a camera lens.

- Determine the f-stop (lens opening) for a given shutter speed to produce correct exposure.

- Given the appropriate equipment, determine image characteristics, using a mirror, Fresnel lens and penta prism; and demonstrate depth of focus.

DISCUSSION

The most popular camera today for many professional applications and for the advanced amateur is the single lens reflex (SLR), which uses a film 35 mm wide (Figure 1). This type of camera has come into wide use for several reasons, the first being its flexibility. A large selection of film types is available for many purposes. It is a simple matter to change lenses from a telephoto lens used to shoot football action from a distant seat, to a wide-angle lens used to record a wide field of view. The SLR feature of reflex viewing (Figure 2) allows the photographer to see exactly what is being photographed and assures that the important parts of the scene are focused sharply.

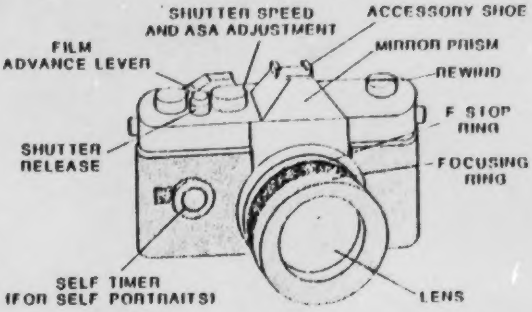

SHUTTER SPEED AND ASA ADJUSTMENT
ACCESSORY SHOE
FILM ADVANCE LEVER
MIRROR PRISM
REWIND
F STOP RING
SHUTTER RELEASE
FOCUSING RING
SELF TIMER (FOR SELF PORTRAITS)
LENS

FIG. 1

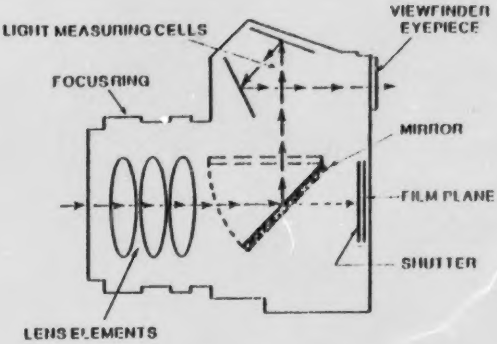

LIGHT MEASURING CELLS
VIEWFINDER EYEPIECE
FOCUSRING
MIRROR
FILM PLANE
SHUTTER
LENS ELEMENTS

FIG. 2

LENSES

The essential features of a simple lens are discussed in Module 13L10. A convex lens (one that is thicker in the center) has the power of converging light rays, or of bringing them to a focused point (Figure 3). Lenses are described by their focal length, the distance f beyond the lens at which parallel rays are brought to a focus. A converging lens has the property of forming a real image (Figure 4) at a distance, called the "image distance," behind the lens. The image distance is determined by the focal length of the lens and its distance from the object, as indicated by Equation 1.

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \qquad (1)$$

where

f = focal length of lens.

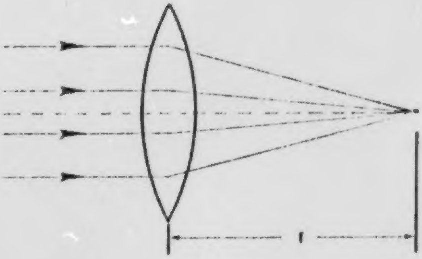
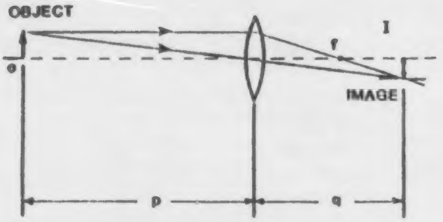


FIG. 3



q=REAL IMAGE DISTANCE

FIG. 4

p = distance from object being photographed to lens.
q = distance from image to lens.

Equation 1 is rearranged in Example A to solve for image distance.

EXAMPLE A: IMAGE DISTANCE

Given: Camera with lens of focal length f = 50 mm and object distance p = 10 m.

Find: Image distance (distance from lens to film).

Solution:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

$$\frac{1}{50 \text{ mm}} = \frac{1}{10{,}000 \text{ mm}} + \frac{1}{q}$$

$$\therefore \frac{1}{q} = 0.0199$$

$$q = 50.25$$

Notice that image distance q differs from f by only 0.25 mm, or 0.5%. For a typical SLR lens of about 50 mm focal length, distances greater than 10 m are large and often marked ∞ (infinity) on camera focusing scales.

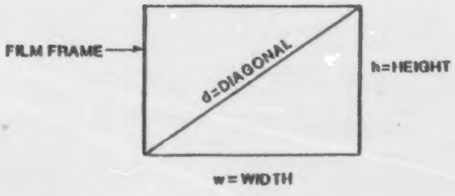


FIG. 5

NORMAL LENSES

A reasonable, or normal, focal length for a camera lens is largely a matter of custom and experience. The accepted "rule of thumb" states that the focal length should be about equal to the diagonal of the film frame, as illustrated by Figure 5 and as expressed by Equation 2.

$$d = \sqrt{w^2 + h^2} \qquad (2)$$

where

d = diagonal of film frame.
w = width of film frame.
h = height of film frame.

Equation 2 is used to solve a focal-length problem in Example B.

EXAMPLE B: NORMAL FOCAL LENGTH

Given: A camera uses 35 mm film (actual frame size for this film format is 24 x 36 mm).

Find: Suggested focal length for "normal" lens.

Solution: Diagonal of the frame is the usual recommendation.

$$d = \sqrt{w^2 + h^2}$$

$$= \sqrt{36^2 + 24^2}$$

$$d = 43 \text{ mm}$$

In actual practice, the normal lenses for 35 mm vary from 40 mm to nearly 60 mm. The diagonal rule is merely a suggestion.

The diagonal rule gives an angle of view of about 50°, which agrees roughly with the angle that the eye takes in when viewing a scene.

The image size appearing on the film is important. A small image does not show up well in relation to the entire frame area and is difficult to enlarge in the photo lab. Calculation of image size for a given lens and distance to object is accomplished by use of Equations 3 and 4.

$$h_i = h_o \left(\frac{q}{p}\right) \qquad (3)$$

where

h_i = image height.
h_o = object height.

Since image distance is equal approximately to focal length for a distant object, Equation 3 can be written as shown in

Equation 4.

$$h_i = h_o \left(\frac{F}{p}\right) \qquad (4)$$

Equation 4 is used to solve a problem in Example C.

EXAMPLE C: IMAGE SIZE ON FILM

Given: Camera with lens of focal length 50 mm. A football player 2.0 m tall is photographed from a distance of 50 m.

Find: Size of image on film.

Solution:

$$h_i = h_o \left(\frac{F}{p}\right)$$

$$h_i = 2000\ \text{mm} \left(\frac{50\ \text{mm}}{50{,}000\ \text{mm}}\right)$$

$$h_i = 2\ \text{mm}$$

TELEPHOTO AND WIDE-ANGLE LENSES

The 2-mm image obtained in Example C is only 2/24 or 8% the height of the 24-mm picture. Even if this small picture were enlarged ten times, the image would be only 2 cm high. The image size formula gives a clue to increasing image size: h_i is directly proportional to the focal length. If the camera were fitted with a lens of 500 mm focal length, the image would be ten times greater. The resulting 20-mm image almost would fill the picture area. Such a long-focus lens is a "telephoto."

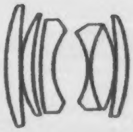


FIG. 6

Aberration can be cured almost entirely by use of lenses having a combination of several lens elements made from different glasses (Figure 6). The proper choice of glasses with the right indices of refraction allows production of complex lenses that have essentially the same focal length for light of all colors. Modern 35 mm cameras are able to take remarkably sharp pictures, with lines and small details clearly defined, larely because of careful lens design, now aided by digital computers to perform the mathematical computations required.

A true telephoto is a combination of lenses, but is more than just a long focal-length combination. It is a special combination of converging front lenses and diverging, or negative, back lenses

(Figure 7). If the combination is turned around (with the diverging lens to the front), the image is formed at a greater distance than the focal length, producing a wide angle lens. For example, a 28-mm lens might be used to photograph a large area (a wide angle) in a confined space — perhaps the wall of a small room.

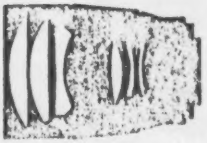


FIG. 7

THE SHUTTER

Recording a good picture on film requires not only a good, clear optical image, but also the proper "exposure." The concept of exposure is related to irradiance, the light energy per unit area falling on the film, and its duration. A camera shutter is merely a gate that controls the time factor of the exposure. There are several types of shutter mechanisms and possible placements with respect to the lens and the film. The principal arrangement used in SLR cameras today is the focal-plane shutter, placed just in front of the film — in the plane where the image is focused.

The focal plane shutter consists of a curtain of metal or of cloth containing one or more slits (Figure 8). The slit moves rapidly across and in front of the film, thereby exposing the film to the pattern of light and dark in the image. The length of exposure time is determined by the width of the slit and by the speed of its motion. The time, or "shutter speed," usually is set by a knob that adjusts the tension of the springs driving the shutter. A simple shutter often is built like a window shade on two rollers. Focal-plane shutters commonly produce exposure times ranging from one second to 1/1000 second. The very short times are useful for "stopping" fast action that otherwise would appear blurred with longer exposures.

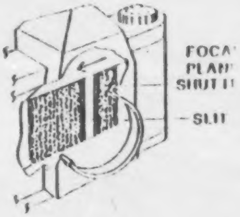


FIG. 8

APERTURE (LENS OPENING)

In all but the very simplest cameras, the amount of light passing through the lens is controlled by a variable, circular opening, or "aperture" control. The lens opening usually is regulated by an arrangement called a "diaphragm" that consists of a set of over-lapping, thin metal leaves. These leaves are opened and closed by the rotation of a ring to which they are linked. A large aperture is associated with a small f-number. For example, a relatively large aperture is f-1.4; a small one, f-16. In the latter case, the focal length is 16 times the aperture diameter.

Lenses generally are marked with f-numbers arranged in a sequence in order that each f-number represents one-half the irradiance of the one before it. A common sequence of f-numbers is as follows:

f-number 1.4, 2, 2.8, 4, 5.6, 8, 11, 16 and 22.

Thus, a camera set at f-5.6 permits 1/2 the irradiance on film as when set at f-4. This difference of a factor of two in irradiance is called a "one stop difference"; f-numbers sometimes are referred to as "stops."

DETERMINING REQUIRED EXPOSURE

Proper exposure depends upon both time and irradiance. The time interval is determined by the shutter and often is referred to as "shutter speed."

The least expensive way to determine the required exposure (f-number and shutter speed) for the lighting conditions is to use the manufactuer's specifications sheet that comes with the film; for example, for a common color slide film (ASA 400) the recommended exposure for "heavy overcast" lighting conditions is f-5.6 at 1/500 second. These simple lighting charts provide good results under "average" conditions.

The next most sophisticated approach is the use of a light meter, or exposure meter, which contains a light-sensitive cell. The ASA film rating is adjusted on a sliding f-stop and aperture scale, allowing a direct reading of a variety of possible f-stop and shutter-speed combinations. Such meters often are built directly into modern cameras, where they measure the exact irradiance on the film.

The highest level of technical sophistication is found in automated cameras. In these cameras, a number of light-sensitive cells sense the irradiance on the film. Built-in electronic circuits then set the aperture and shutter speed automatically.

FILM

Photographic films are produced in many different types: black and white, color slide, color print, and polaroid. A major property of all films is their sensitivity, or "speed." Sensitivity refers to the amount of exposure required to produce a satisfactory, permanent image on the film. In the United States, the sensitivity of films is rated in terms of a scale called the "ASA system," established by the American Standards Association. Film manufacturers conduct experiments to determine the sensitivities of their films, and assign an ASA number that best describes their behavior.

The light-sensitive layer of a film is called the "emulsion," which is a complicated mixture of silver salts, dyes, and other chemical compounds tailored to give the desired speed and other properties. A permanent image is formed on film emulsion by the interaction of light photons with silver atoms in the emulsion. Modern emulsion chemistry has produced films uniformly sensitive to all colors.

EXAMPLE G: EXPOSURE AND ASA NUMBER

Given: An exposure meter indicates that the recommended exposure for a certain subject is f-5.6 at 1/500 s, with a film emulsion rated at ASA 400.

Find: The correct exposure for this subject with a film of ASA 100.

Solution: A film of ASA 100 is 1/4 as sensitive as a film of ASA 400, and therefore requires four times the exposure. These are some suitable choices:

f-5.6 at 1/125 s (increasing exposure time 4X)
f-2.8 at 1/500 s (increasing aperture area 4X)
f-4 at 1/250 s (increasing time and aperture each 2X)

VIEW FINDERS AND REFLEX VIEWING

Any camera must have some kind of view finder to indicate what scene is being recorded. The simplest finder is merely a pair of wire rectangles to mark off approximately the area being covered. Many cameras now use optical view finders, which consist of a converging lens followed by a diverging lens.

Probably the best view finder is the single-lens reflex type, illustrated in Figures 1 and 9. The reflex arrangement is desirable because it uses the camera lens to form an image on a viewing screen by way of a mirror. Reflex viewing allows the photographer to see exactly what the film will record, including focus. Another great advantage of reflex viewing is "parallax correction," an automatic adjustment that corrects the "head room" for objects being photographed at any distance.

As illustrated by Figure 9, the modern 35 mm SLR camera includes a 45° mirror that reflects the image to a horizontal viewing screen. The viewing system also contains a Fresnel lens that increases illumination. The Fresnel lens, as indicated in Figure 10, is designed with ridges that produce a brighter image through the viewing system. Such a lens is not suitable as the primary lens, but it is useful as an aid to viewing, especially in dim light.

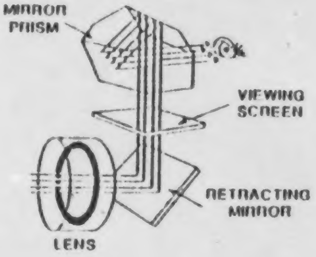


FIG. 9

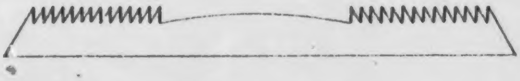


FIG. 10

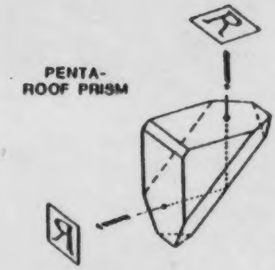


FIG. 11

The mirror prism (Figure 11) has seven internal reflecting surfaces. The two "roof" mirrors interchange left and right, so that the SLR user sees a clear, bright image, in which all the directions are shown properly.

FOCUSING

The simplest approach to focusing used in the cheapest cameras, is called "fixed focus." The lens-to-film distance is set permanently to give a reasonably sharp image at an average object distance — usually about nine feet. Objects at greater distances are well focused; closer objects are less well focused. This approach is satisfactory only with simple cameras having lenses of short focal length and small aperture.

Modern single-lens reflex cameras are focused by rotation of the lens tube. (Small lens openings, like f-16, allow greater "depth of field," or range of correct focus, than large ones.) Automatic-focus lenses now are available on some models.

SUMMARY

The single lens reflex camera, like other cameras, records the pattern of light falling on the film. The same lens which focuses this radiation on the film is first used to view the scene, and then to adjust metering and focusing. Exposure and focus settings are made automatically on some high-priced cameras.

IMAGE CHARACTERISTICS

MATERIALS

Light bulb marked with vertical and horizontal arrows of black plastic tape.
Convex lens, having focal length of several inches.
Plane mirror.
Translucent material — ground glass, oiled paper, or rear projection material, such as Edmund #70,934 — about 2" x 2".
Fresnel field lens, such as Edmund #30,389.
Penta roof prism (five-mirror prism) such as Edmund #3259.

PROCEDURE

1. Refer to Figure 12, and set up object (small light bulb with vertical and horizontal arrows of tape).
2. Support convex lens on optical bench, if available. Otherwise, hold in vertical position on table by any convenient means.
3. Support pieces of translucent material in vertical position, as in Figure 12.
4. Adjust positions of lens and screen to give sharp image on screen.
5. Record image data, in terms of orientation and brightness, in Data Table 1.
6. Mount mirror at 45° to horizontal, as shown in Figure 13. Support translucent screen horizontally above mirror. Adjust positions to give sharp image of bulb. Support screen with ring stand and clamp.
7. Record image data.

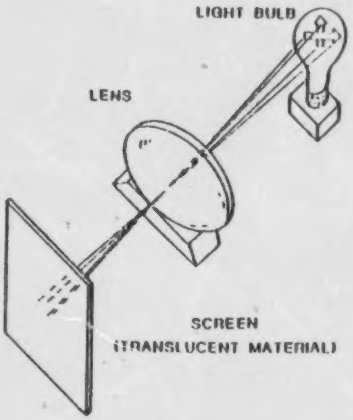


FIG. 12

8. Replace screen with Fresnel (rough side nearest mirror).

9. Record image data.

10. Place roof penta prism on top of screen, as shown in Figure 14. Observe image looking horizontally into prism. Record image data.

11. How does the image data obtained using the mirror, Fresnel lens, and penta prism demonstrate the actual operation of a single lens reflex camera?

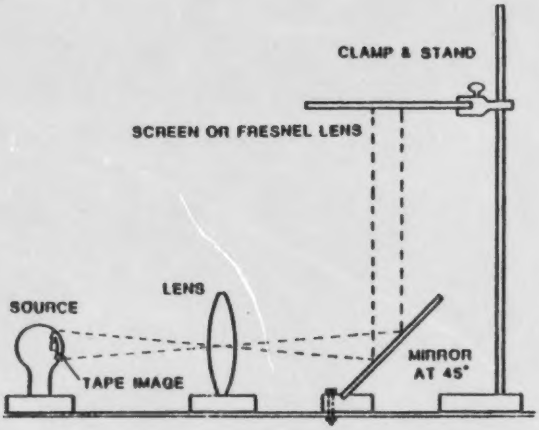

CLAMP & STAND
SCREEN OR FRESNEL LENS
LENS
SOURCE
TAPE IMAGE
MIRROR AT 45°

FIG. 13

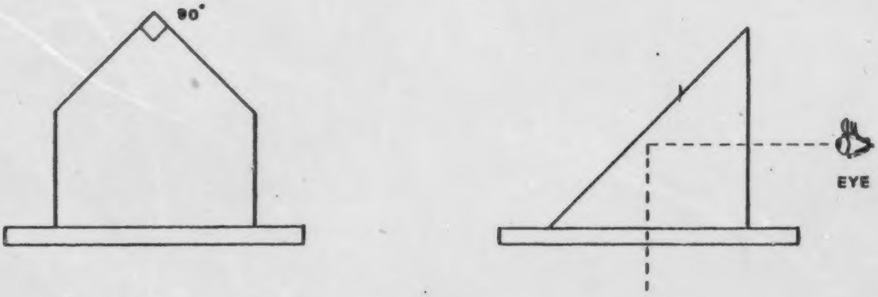


FIG. 14

DEPTH OF FOCUS

MATERIALS

Simple Polaroid camera — one of the following models: Super Shooter, 430, 440, 450; Minute Maker; or Reporter. (Do not use the SX-70.)

Polaroid Type 107 black-and-white film. Flash bulbs or strobe, if required because of poor lighting.

Five cards or sticks, at least 6" in height, marked with stripes approximately 1/2 in apart.

PROCEDURE

1. Set up marked cards or sticks at distances of 5, 10, 15, 20, and 25 ft.

2. Take one exposure containing the five markers, with camera focusing scale set at 3 ft. Allow film to develop the normal 15 seconds. Record applicable data for each photograph in Data Table 2.

3. Repeat Step 2 with focusing scale set first at 10 ft, then at infinity. Record results.

4. When the camera is focused for 10 ft and a picture is taken, why does the 15-ft marker appear to have greater sharpness (or greater depth of field) than the 5-ft marker, although both are only 5 ft from the 10-ft marker?

DATA TABLE 1

Image Data	Mirror 45° to Horizontal	Fresnel Lens	Penta Prism
Erect?			
Inverted?			-------
Reversed (left for right)?			
Correctly oriented?			-------
Bright or dim?			-------
Evenly illuminated?			-------
If not evenly illuminated, how does brightness vary?			-------

DATA TABLE 2				
Exposure Number	Marker Distance (ft)	Sharpness (Check one)		
		Very Sharp	Blurred	Very Blurred
1 Camera Focus, 3 ft	5			
	10			
	15			
	20			
	25			
2 Camera Focus, 10 ft	5			
	10			
	15			
	20			
	25			
3 Camera Focus, Infinity	5			
	10			
	15			
	20			
	25			

SELF CHECK

1. Answer the following questions about the single lens reflex camera:
    a. What is a SLR camera?
    b. What is the difference between a normal lens and a wide-angle or telephoto lens?
    c. How is shutter speed controlled?
    d. What is a large aperture?
    e. How does a photographer use ASA numbers?
    f. Does reflex viewing indicate use of the camera lens?
2. What is the approximate focal length of a normal lens having a film frame of 2 1/4" x 2 1/4"?
3. In order to maintain a constant exposure when the shutter speed is cut in half, how must the f-stop number be changed?

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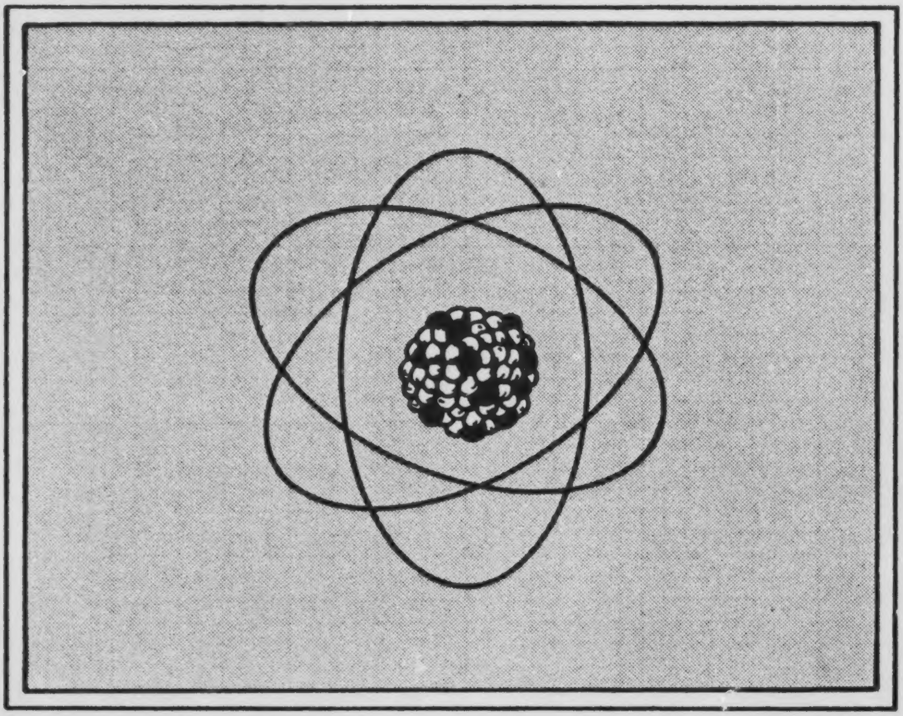
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 13 N 1
GEIGER COUNTERS



RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Nuclear radiation passing through certain gases produces ionization. The resulting charged particles can be collected and measured to indicate the presence and amount of radiation. The Geiger counter is an application of this method of radiation detection and measurement. The purpose of this module is to investigate the characteristics and use of the Geiger counter in measuring radiation. In the laboratory, the student will determine the operating voltage of a Geiger counter and will measure ionizing radiation produced by a radioactive source.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the major components of a portable Geiger counter.
- Describe the operating characteristics of a Geiger-Müller detector, including the following:

  Ionization.
  Cascade or Avalanche Effect.
  Collection of Charge.

- Describe the types of radiation that can be measured by a Geiger counter, and give the units of measurement.
- Graph the characteristic curve for a Geiger-Müller detector, indicating the "starting potential," the threshold voltage, the "plateau," and the region of continuous discharge.
- Given the appropriate equipment, determine operating voltage of a Geiger detector; and measure ionizing radiation produced by a radioactive source.

DISCUSSION

The Geiger counter is an instrument that detects and measures radioactivity by counting electrical discharges caused by the passage of nuclear particles through a gas in a detector. Figure 1 displays a portable Geiger counter, consisting of the following items: A probe detector (Geiger-Müller tube) attached by power leads to a chassis circuit containing a power supply, control for variable time constant, range switch, and meter scale for reading counts per minute. Most units also contain a speaker that audibly indicates each count as a "click."

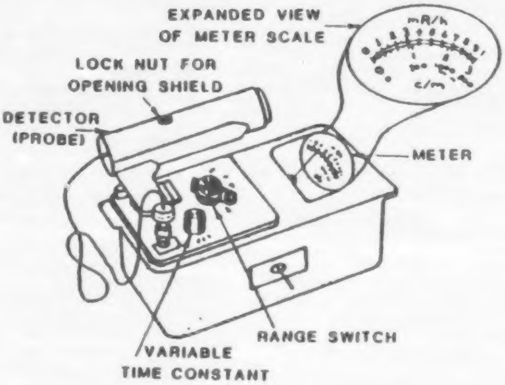


FIG. 1

Some Geiger counters are designed for laboratory use. For example, the scaler/detector illustrated in Figure 6 and used in the laboratory procedure provides a digital readout of the counts.

GEIGER-MÜLLER DETECTOR TUBES

The Geiger-Müller (GM) detector tube is constructed of two electrodes, surrounded by a gas that can be ionized easily. Nuclear radiation passing through the gas produces ionization, resulting in charged particles. The charged particles then are attracted to the electrodes of opposite charge. As they move toward these electrodes, they produce a current. This current then can be measured and recorded by an electronic scaler. Each particle or ray of radiation passing through the GM tube ionizes the gas within, creating a pulse of current. These pulses provide a measure of the intensity of the radiation.

Geiger-Müller detectors are produced in a variety of types, a common one being the "end window" type (Figure 2). This tube is called an "end-window" type because of the thin window at one end, through which the radiation passes.

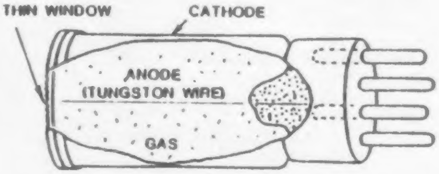


FIG. 2

The tube is a metal or glass cylinder coated inside with a conducting material. This cylinder, or outer wall, constitutes the negative electrode, known as the "cathode." A fine tungsten wire stretches along the center of the tube. This wire is the positive electrode, or "anode." The space between electrodes contains a gas such as helium or argon, which provides the ionizing medium. The "end-window" seals the tube, preventing escape of the gas and allowing the passage of radiation. The area inside the tube is called the "sensitive" region, or volume.

Geiger-Müller tubes are not equally sensitive to all types of ionizing radiation, due to the properties of the tube and of the radiation. Since radiation must enter the sensitive region to be detected, alpha particles usually cannot be detected, because they are absorbed in the window or tube wall. Beta particles usually are detected easily with the "end-window" type or other thin-window types of GM tubes. Gammas are the most energetic of the three ionizing radiations. They are detected easily, although efficiency of detection may be low since they often pass completely through the sensitive volume without causing much ionization.

As illustrated by Figure 3, when gamma or beta radiation enters the sensitive volume, it produces ion pairs; that is, electrons and positively-charged ions within the gas present in the tube. Since atoms within the gas are struck by incoming gamma and beta particles, they release electrons and positive ions. The potential difference between the cathode and the anode causes electrons to move toward the positively-charged center wire (anode) and the positive ions to move toward the negatively-charged tube walls (cathode).

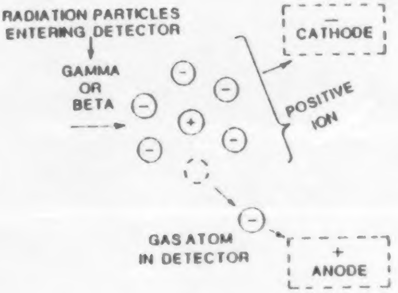


FIG. 3

Energy is acquired by the charged particles as they accelerate; therefore, subsequent collisions with other gas molecule cause further ionization. This process is repeated many times, resulting in a "cascade," or "avalanche," effect. Thus, once ionization is initiated, it continues to produce further ionization until "quenched" (turned off). Quenching results from the addition of a special gas, such as chlorine or bromine, which absorbs some of the energy of the accelerated ions or electrons. One of the important advantages of GM detectors over other types is the formulation of a large electrical pulse caused by the many ion pairs produced in the initial ionization and subsequent avalanche phenomena.

A typical Geiger counter circuit is illustrated in Figure 4. A variable, high-voltage supply is used to obtain proper operating voltage. The cathode is at ground (zero) potential whenever a positive charge is placed on the anode. Capacitor C_1 blocks high voltage from the counter, and resistor R_1 permits voltage on the anode to drop when negative ions are collected. Ions are collected

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by isolating or separating the high-voltage supply from the anode. (C_2 represents the total counter capacitance, and R_2 refers to counter-circuit resistance.)

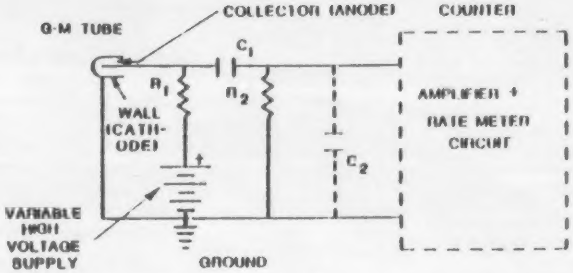


FIG. 4

Operation of a GM detector is indicated by a characteristic curve, as shown in Figure 5. If a radioactive sample is placed near the end-window of a GM tube and if the voltage on the tube is slowly increased, a point will be reached at which radiation entering the sensitive volume is indicated by counts on an electronic scaler. This point, called the "starting potential" (usually about 700 V), is the point at which there is enough potential difference to accelerate the electrons and ions fast enough to cause further ionization (secondary ionization), and thus to create enough charge to provide a significant charge or voltage pulse to drive the scaler. If the power supply voltage then is increased further, the counts detected will begin to increase very quickly for relatively small increases in voltage, reaching a so-called "threshold" voltage (Figure 2).

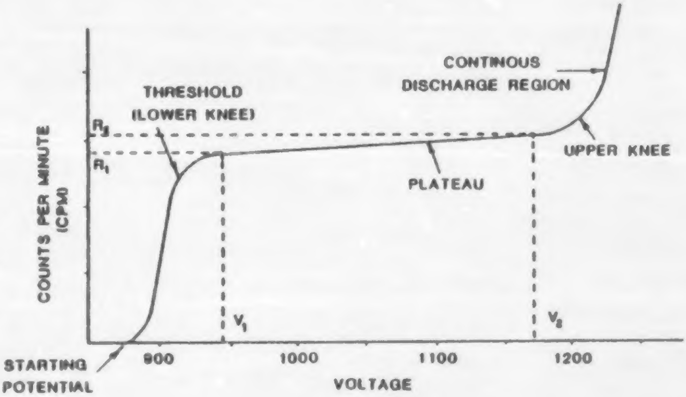


FIG. 5

Beyond this "threshold" lies the "plateau" at which significant increases in voltage do not result in significant changes in count rate. This plateau usually ranges from 900 V to 1100 V and is a relatively flat region on the characteristic curve. The optimum operating voltage for GM detectors lies within the voltage range defined by the plateau, with the ideal voltage located in the lower 25% of the plateau region, where the curve exhibits minimum slope. Since most power-supply voltages change due to spurious causes, the GM tube must be operated in the plateau region. In the plateau, a change in counts registered is caused by a change in radiation intensity, not by a spurious change in power-supply voltage. Thus, operation in the plateau ensures accurate counts of the incoming radiation.

Further increases in voltage past the plateau region result in continuous discharge of the tube, as indicated by a continuous and rapid registering of counts. Operation in this region, for even a short period of time, can damage the detector seriously and permanently.

For radiation actually reaching the sensitive volume of the GM tube, the efficiency of detection and measurement is essentially 100% for alphas, 80 - 100 % for betas, and 1 - 8% for gammas, because of the difference in penetrating power of each type of radiation. The window for "end-window" GM's is relatively thin, usually made of mica or mylar to ensure minimum absorption of radiation. Side-window GM's have a much thicker window, rendering them essentially useless for detecting alphas, but still quite efficient for detecting energetic betas and gammas. The type of GM tube selected depends, therefore, upon the type and form of radiation to be detected and measured.

SUMMARY

The Geiger counter is an important instrument used in the detection and measurement of radiation. The Geiger-Müller detector, a gas-filled tube, detects radioactive particles, or rays, which ionize the atoms of the gas, thereby producing electrical pulses that are registered to determine the intensity of radiation.

LABORATORY

DETERMINATION OF OPERATING VOLTAGE

MATERIALS

One "end-window" Geiger-Müller detector.
Electronic scaler and high-voltage power supply.
Sample holder/counting stand.
Radioactive beta or gamma source (Cs^{137} or Co^{60}).

PROCEDURE

Although there are many brands and models of scalers, they are basically the same in operation; therefore, the following general directions apply to any scaler used. Figure 6 shows a typical scaler-detector holder setup.

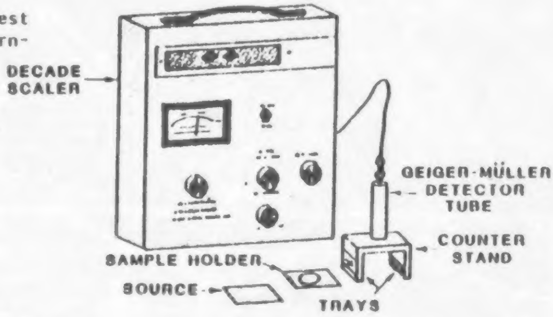


FIG. 6

1. Adjust high voltage to lowest possible setting before turning on power supply.

2. Connect GM tube to proper input jack. If ready-made cables are not provided for connecting GM tube to scaler, connect anode to positive terminal and cathode to negative chassis (ground).

3. Turn on scaler, and allow two minutes minimum warmup time.
   CAUTION: GM windows are extremely thin and very delicate. Do not bump them against any other object. High voltages will be applied to the tube, requiring great caution in positioning the source and in manipulation or placement of laboratory equipment.

4. Clear (or reset) scaler, and place source in sample holder/counter stand tray nearest to GM tube. Important: maintain same source-to-detector distance throughout experiment.

5. Turn on scaler, press start or "start count" button (switch), and slowly increase high voltage, observing count rate until

700 V is reached. At 700 V, reset scaler and begin counting for two-minute period. Record number of counts and voltage setting in Data Table 1.

6. Increase high voltage to 750 V; wait one minute, and then reset scaler and take another two-minute count, recording same information as before. Continue in same manner, increasing voltage in 50-V increments and recording the same information, until 900 V is reached.

7. Beginning at 900 V, increase high voltage in 25-V increments, waiting one minute, resetting scaler, and counting for two minutes, recording the same information. Continue until there is a significant increase in count rate for 25-V increment compared to the previous increments. Care is required here since operation, in the region of continuous discharge (Figure 5), can damage the GM tube permanently.
Caution: To prevent damage do not permit count rate to increase more than 10 to 15% above that for the plateau region. (Refer to Figure 5.)

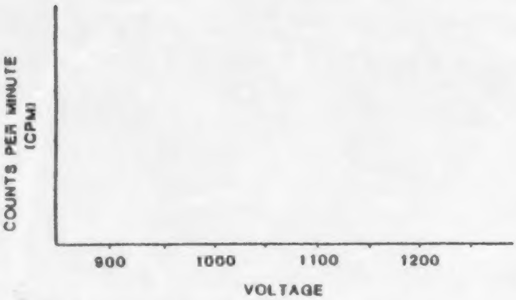


FIG. 7

8. Use Figure 7 graph to plot count rate (y-axis) versus voltage (x-axis) for information collected in above procedure, and determine the optimum voltage for operation of GM tube used in this experiment, indicating it on Figure 7 graph. How does it compare with voltage stamped on tube? List optimum voltage determined in Data Table 2.

9. Set high voltage to this experimentally-determined operating voltage; wait one minute, reset scaler, and take a two-minute count to ensure stabilized operation at this voltage. Take five, two-minute counts at this voltage, recording each count in Data Table 2. Compare the number of counts for each of the five two-minute intervals. Is count rate stable? How does it compare with initial data used for plotting the characteristic curve? Explain any differences.

DATA TABLE 1

EQUIPMENT AND SOURCE DATA

Tube Identification No: __________

Tube Type ("end-window"; quench gas): ____________________

Operating Voltage (Stamped on Tube): __________

Scaler Identification No: ______________________

Radioactive Source Type: ______________________

TEST DATA

VOLTS	COUNTS IN TWO MIN	VOLTS	COUNTS IN TWO MIN	VOLTS	COUNTS IN TWO MIN
700		950		1100	
750		975		1125	
800		1000		1150	
850		1025		1175	
900		1050		1200	
925		1075		1225	

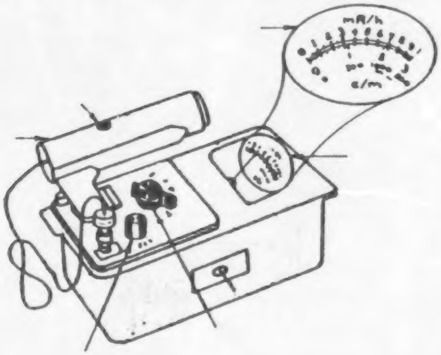
Note: To obtain counts per minute (cpm), divide total counts registered in two-minute interval by two.

DATA TABLE 2

OPTIMUM VOLTAGE (Fill in from Step 8)	NUMBER OF COUNTS IN TWO MINUTES				
	Test 1	Test 2	Test 3	Test 4	Test 5

SELF CHECK

1. Label the major components of a portable Geiger counter on the following drawing.



2. Describe the operation of a Geiger-Müller detector, how it is constructed, and how nuclear radiation is detected by gas ionization. What is the "cascade," or "avalanche," effect? How is electrical charge created in a GM tube, collected, and measured?

3. What types of radiation (particles or rays) can be detected with the GM detector? What are the units of measurement of radiation when using a GM detector?

4. Sketch a characteristic Geiger-Müller detector curve indicating the starting potential, threshold voltage, operating plateau, and the region of continuous discharge.

5. For the above characteristic curve, how is the best operating voltage determined?

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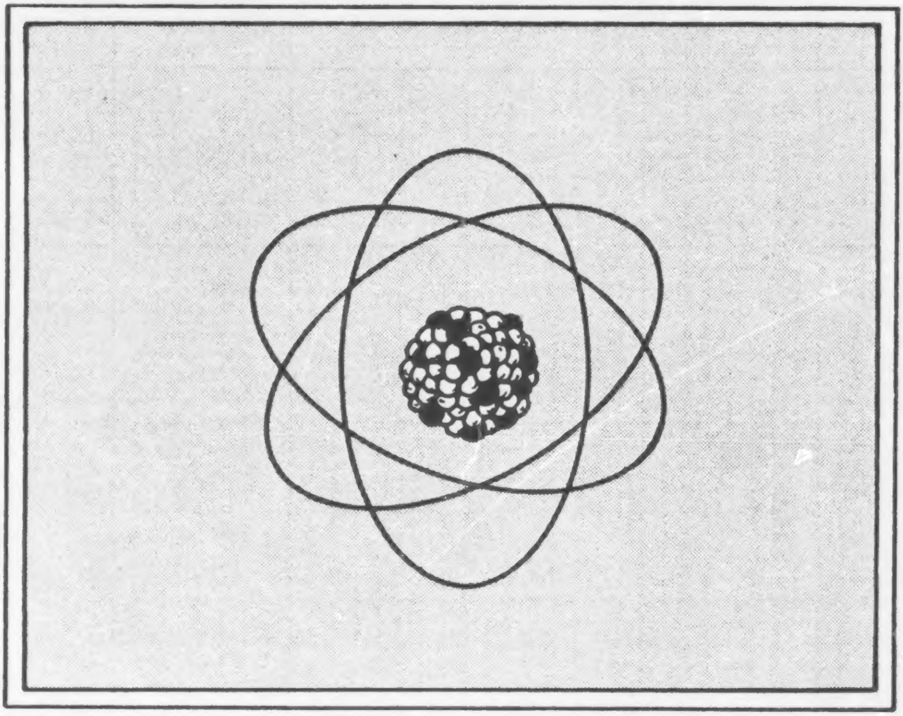
UNIFIED TECHNICAL CONCEPTS

MODULE 13 N 2

PENETRATING POWER OF ALPHA AND BETA RADIATION



RADIATION

Technical Education Research Center - Southwest

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INTRODUCTION

Alpha radiation and beta radiation are particulate types of radiation. An alpha particle is the nucleus of a helium atom -- two protons and two neutrons. A beta particle is an electron. Both types of particles lose energy as they pass through a material because they collide with the electrons in the material and give up energy to them. Eventually, all the particle energy is lost, and the particle comes to rest, after having passed through some distance in the material. This distance is the "range." In this module, we will learn how the range of alpha and beta particles depends upon their energy. In the laboratory, the student will measure the range for both alpha particles and beta particles.

PREREQUISITES

The student should have completed Concept Module 13-0, "Radiation"; and Application Modules 13N4, "Absorption of Gamma Radiation," and 13N1, "Geiger Counters."

OBJECTIVES

Upon completion of this module, the student will be able to:

- Define alpha and beta radiation, including the mass and charge for each.
- Describe the processes by which alpha and beta particles lose energy in absorbing materials.
- For alpha particles, define "mean range," "range straggling," and "stopping power."
- For beta particles, describe the shape of the absorption curve, define "maximum range," and state the approximate relation between maximum range and energy.
- Given the necessary equipment, measure the range for alpha particles in three different absorbing materials.
- Given the necessary equipment, measure the penetration of beta rays through various thicknesses of absorbing material,

and determine the maximum range. Use the result to determine the maximum energy of the beta rays from the source that was used.

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DISCUSSION

ALPHA PARTICLES

Alpha radiation and beta radiation are particulate types of radiation; that is, they consist of small (atomic-scale) particles that have mass and electrical charge. In contrast, gamma radiation is electromagnetic in nature, but has neither mass nor electrical charge. Both alpha and beta radiation are produced in the radioactive decay of unstable atoms. The relation of these types of radiation to radioactivity will be described in Module 13N3, "Radioactivity."

Alpha particles are the nuclei of helium atoms; that is, they are formed of two protons and two neutrons bound together. An alpha (α) particle, therefore, is a helium atom with its two electrons removed. Alpha particles have a finite, measurable mass equal to 6.62×10^{-24} gm. They also carry a positive electrical charge, equal to 3.20×10^{-19} coulomb. This value is two times the basic electrical charge of the electron.

The alpha particles emitted in a particular radioactive decay have definite energies. The energies of alpha particles vary from about 4 MeV to about 9 MeV. A particular radioactive isotope in its decay produces an alpha particle having a well-defined energy. The energies of the alpha particles from the decays of several different isotopes are listed in Table 1. All the radioisotopes listed are found in nature. For a given element, there may be several different isotopes that emit alpha particles; for example, the element polonium (Po) is represented by five different isotopes, each of which produces an alpha particle with a different energy.

(Recall that for a given chemical element, different isotopes have different numbers of neutrons in the atomic nucleus. In Table 1, the isotopes are denoted by the chemical symbol for the element, with the mass number as a superscript. The mass number is equal to the sum of the neutrons and protons in the nucleus.)

TABLE 1. ALPHA PARTICLE ENERGIES FROM SOME NATURALLY OCCURRING RADIOISOTOPES

Isotope	Alpha Particle Energy (MeV)
U^{238}	4.19
Th^{232}	4.35
U^{235}	4.74
Pa^{231}	5.11
Bi^{214}	5.51
Ra^{224}	5.68
Po^{218}	6.00
Bi^{211}	6.62
Po^{215}	7.38
Po^{211}	7.45
Po^{214}	7.68
Po^{212}	8.78

BETA PARTICLES

Now we turn to the beta particle, often denoted as the β particle. Beta radiation also originates in the decay of unstable atomic nuclei, like alpha radiation; however, it has a different nature and different properties than alpha radiation. The beta particle is an electron, the same as the electrons in orbit around the nucleus of an atom. The beta particle has the same mass as other electrons, 9.11×10^{-28} gm, a mass much smaller than that of the alpha particle. The electrical charge is 1.60×10^{-19} coulomb (4.80×10^{-10} electrostatic units), and it is negative (opposite in sign to the charge of the alpha particle). Notice that this value is equal to the basic unit of electronic charge.

The energies of beta rays emitted by an unstable atomic nucleus cover a range of values, up to some maximum value characteristic of that nucleus. Thus, beta-ray energies form a spectrum. An example of the energy spectrum of the beta rays from the radioisotope Bi^{210} is given in Figure 1. This figure depicts the relative number of beta rays emitted as a function of energy. The spectrum has a peak near 0.15 MeV. The decay of an atom of Bi^{210} may yield a beta ray of any energy, between zero and the maximum energy, which in this case is 1.17 MeV. The most probable value of the energy is 0.15 MeV.

The energies of beta-ray spectra extend up to a few MeV. Table 2 lists the maximum beta-ray energy for several different radioisotopes. All these isotopes are naturally occurring ones. In each case, the spectrum is characterized by the maximum value of the energy.

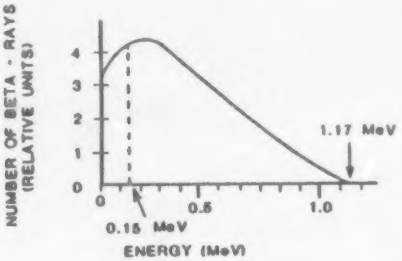

FIG. 1

TABLE 2. BETA PARTICLE ENERGIES FROM SOME NATURALLY OCCURRING RADIOISOTOPES

Isotope	Maximum Beta Particle Energy (MeV)
Pb^{214}	0.72
Bi^{210}	1.17
Fr^{223}	1.20
Pb^{211}	1.40
$\mathrm{T\ell}^{207}$	1.47
Ac^{228}	1.55
$\mathrm{T\ell}^{207}$	1.82
K^{40}	1.90
Pa^{234}	2.32

The occurrence of a spectrum of energies for beta particles is in contrast to the behavior of alpha particles. For a particular radioisotope, the alpha-ray energy will be fixed, having one particular value (see Table 1), rather than a distribution of energies.

For summary purposes, a comparison of the properties of alpha, beta, and gamma radiation is presented in Table 3.

TABLE 3. COMPARISON OF PROPERTIES OF ALPHA, BETA, AND GAMMA RADIATION

Type of Radiation	Nature	Mass (gm)	Electrical Charge (coulomb)
Alpha	Helium atom nucleus	6.62×10^{-24}	$+ 3.20 \times 10^{-19}$
Beta	Electron	9.11×10^{-28}	$- 1.60 \times 10^{-19}$
Gamma	Electromagnetic Radiation	0	0

ALPHA AND BETA PENETRATION

Both alpha particles and beta particles are charged particles that interact with the electrically-charged electrons and nuclei in a material. They start with some value of velocity and gradually lose energy through a series of interactions in which energy is transferred to the electrons and atoms in the material. When all the kinetic energy of motion has been dissipated, each particle comes to rest. Eventually, it will combine with a particle of opposite electrical charge and become a neutral atom. For example, after the alpha particle has slowed down sufficiently, it will attract and combine with two free electrons and become a neutral helium atom. This is possible because there are always a few free electrons around, generated by the natural background of radiation.

This slowing down and gradual loss of energy of α and β particles is different from the behavior of gamma rays, as discussed in Module 13N4. Gamma rays are absorbed in one sudden interaction, rather than gradually giving up energy in a series of interactions with many electrons.

PENETRATION OF ALPHA PARTICLES

Alpha particles produce intense ionization as they pass through a material. They knock electrons out of the atoms in the material and, in the process, transfer small amounts of energy to the electrons. The result is a track of ions and electrons along the path of the alpha particle. Gradually, the alpha particle gives up all its kinetic energy and essentially comes to rest.

The thickness of absorbing material which the alpha particle traverses before coming to rest is the range of the alpha particle in that material. For a given material and a given initial energy, the range of the alpha particle is well defined. Figure 2 is a schematic diagram of the fraction of alpha particles that penetrate to a given depth R in a material. The curve is flat up to a certain value, beyond which it drops rapidly and falls to zero.

The mean range of the alpha particle, denoted R_0 in Figure 2, is the thickness of material that stops 50% of the incident alpha particles.

The form of the curve in Figure 2 is much different from the form of the corresponding curve for gamma rays. For gamma rays, the curve is continuously decreasing, with an exponential shape, and has no flat region. It does not ever go completely to zero, as does the alpha-particle curve.

There is a small uncertainty in the range of alpha particles because of statistical fluctuations in the loss of energy near the end of the range. Thus, all the alpha particles of a given energy do not have exactly the same range. This phenomenon is called "straggling." The amount of straggling is denoted by ΔR in Figure 2. For alpha particles of reasonable energy, the straggling ΔR is generally small compared to the mean range. NOTE: Because of straggling, all the alpha particles will not have exactly the same range. Rather, the range for a particular alpha particle will have a value close to the mean range.

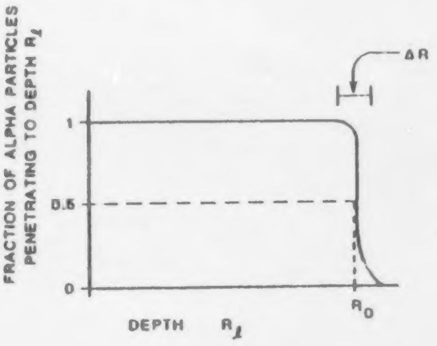

FIG. 2

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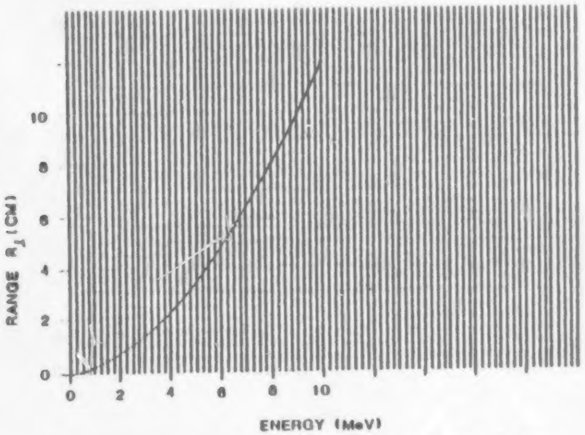
The rate of energy loss, of course, determines the range. This leads to the concept of "stopping power," defined as "the energy lost by an alpha particle as it travels unit distance through a material." The stopping power is a complicated function of alpha-particle energy and of the properties of the absorber; a complete description of the dependence of the stopping power is beyond the scope of this module.

The stopping power is proportional to the number of electrons per unit volume in the material; consequently, materials of high density (which have more electrons per unit volume) will have higher values of stopping power — and, hence, lower values of range — than do materials of low density.

The values of range now can be qualified by the presentation of some results for specific materials. Figure 3 depicts the mean range as a function of energy for alpha particles in air. For reasonable values of alpha-particle energy (a few MeV), the range is only a few cm, much shorter than the range of gamma rays of similar energy.

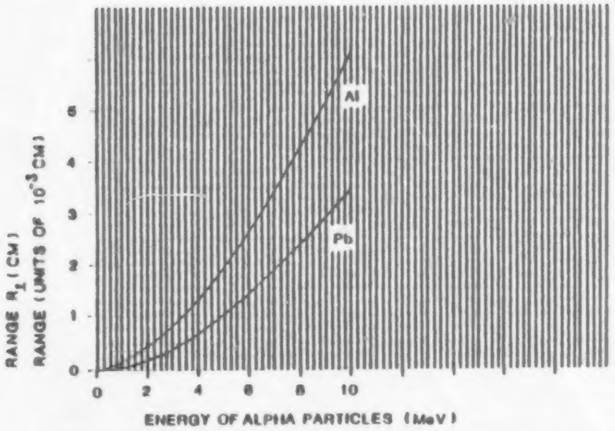


MEAN RANGE VS. ENERGY FOR ALPHA PARTICLES IN AIR

FIG. 3

Figure 4 displays mean range as a function of energy for alpha particles in aluminum (Al) and lead (Pb). The values of range are much smaller than those in air, because of the higher density of aluminum and lead.

In Figures 3 and 4, the range is expressed in units of length (cm). As was the case with gamma rays, the range also can be expressed in units of mass per unit area. The relation between



MEAN RANGE VS. ENERGY FOR ALPHA PARTICLES IN LEAD AND ALUMINUM

FIG. 4

these two expressions of range is given by Equation 1.

$$R\ (\text{gm/cm}^2) = R_\ell\ (\text{cm})\ \rho \qquad (1)$$

where

R = range in units of mass per unit area (gm/cm^2).
R_ℓ = range in units of length (cm).
ρ = density of the absorbing material (gm/cm^3).

In practice, range relations often are expressed in units of gm/cm^2.

As the following example of the use of Equation 1 demonstrates, the range for an alpha particle of a given energy shows less variation between materials when it is expressed in these units.

EXAMPLE A: RANGE OF AN ALPHA PARTICLE

Given: The densities of air, aluminum, and lead are 1.29×10^{-3}, 2.7, and 11.48 gm/cm^3, respectively.

Find: The range of 5 MeV alpha particles in (a) air, (b) aluminum, and (c) lead, expressed in gm/cm^2.

Solution: (a) For air, use Figure 3 to obtain range R_ℓ = 3.5 cm at 5 MeV. Use Equation 1:

$$R\ (gm/cm^2) = R_\ell\ (cm)\rho$$

$$R = (3.5)(1.29 \times 10^{-3}) = 4.52 \times 10^{-3}\ gm/cm^2$$

(b) For aluminum, Figure 4 gives $R_\ell = 1.85 \times 10^{-3}$ cm at 5 MeV, and $R = (1.85 \times 10^{-3})(2.7) = 5.0 \times 10^{-3}\ gm/cm^2$.

(c) For lead, Figure 4 gives $R_\ell = 1.10 \times 10^{-3}$ cm at 5 MeV, and $R = (1.10 \times 10^{-3})(11.48) = 12.6 \times 10^{-3}\ gm/cm^2$.

This example illustrates that for alpha particles of a given energy, the range does not vary so much between different absorbing materials when it is expressed in units of mass per unit area.

PENETRATION OF BETA PARTICLES

Beta particles lose energy by interacting with the electrons in the material through which they pass. Like alpha particles, they interact with the electrons because of their electrical charge. They give up their energy in small amounts in each interaction, leaving behind a track of ionized particles. Unlike alpha particles, beta rays often change the direction of their motion when they collide with electrons or atoms in the material. This happens because the mass of the electron is much less than that of the alpha particle. Alpha particles passing through a material are rarely deflected. A crude analogy might be a ping pong ball and a bowling ball: the course of a ping pong ball is deflected much easier than that of the bowling ball.

Because electrons (beta rays) often are deflected from their direction of travel, they often do not penetrate deeply into a material. Instead, their path is marked by erratic changes of direction. Thus, the absorption curve for beta rays is much different from that of alpha rays. Figure 5 shows a schematic diagram of how a beam of electrons is attenuated in a material. The figure illustrates the fraction of electrons (all initially at the same energy) that penetrate to a given depth in the material. Because of collisions that cause the electrons to change their direction (although they have not given up all their energy), not many electrons penetrate to the maximum depth. The form of the curve differs greatly that in Figure 2 for alpha particles. Because the curve slopes continuously downward, a mean range cannot be defined in the same way as for alpha particles; rather, there is the maximum range beyond which no beta rays penetrate. This maximum range is the depth at which the beta ray has given up all its energy, even if it has experienced no change in direction.

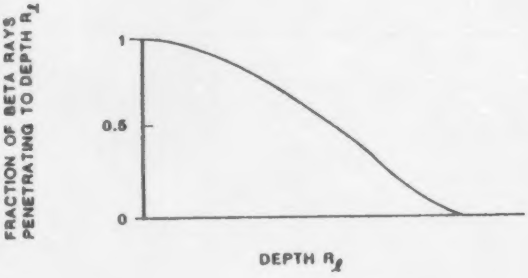


FIG. 5

The situation for beta rays emitted from a radioactive isotope is even more complicated because these beta rays exhibit a spectrum of energies. Thus, the absorption curve is defined by contributions from beta rays having a continuous range of energies. The shape of the absorption curve changes to that shown in Figure 6. As compared to Figure 5, more beta rays are stopped at short ranges because the beta-ray energy spectrum peaks at relatively low energy (Figure 1). The low-energy electrons are removed first, near the surface of the absorber. Beta rays from the high-energy portion of the spectrum penetrate deeper. The maximum range is defined by electrons of maximum energy in the beta-ray spectrum. Because there are relatively few electrons at the upper end of the energy spectrum, the curve in Figure 6 tails off to zero very gradually, making difficult the measurement of the upper end of the range of beta rays emitted by a given radioisotope.

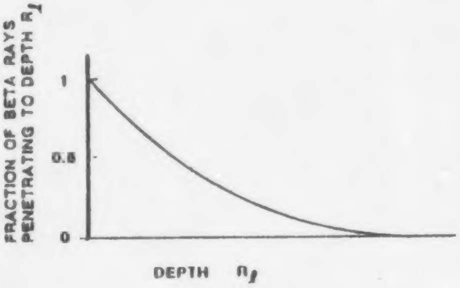
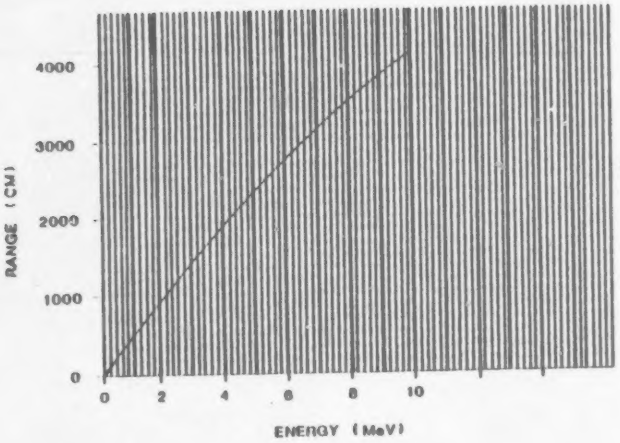


FIG. 6

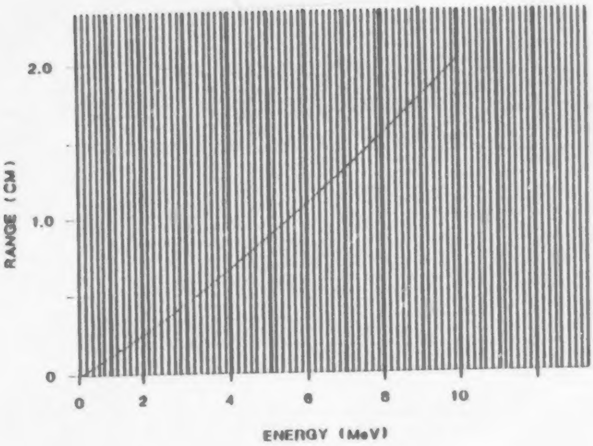
The range-energy relation for beta rays in air is given by Figure 7. The range shown in the figure is the maximum range for beta rays having the given value of energy (or for a beta ray spectrum with the given value of energy as its upper limit). The results are to be compared with Figure 3, which presents the mean range for alpha particles in air. The beta ranges are seen to be much greater for a particular value of energy.

Beta-ray range in aluminum as a function of energy is shown in Figure 8. The range is the maximum range for beta rays of the given energy. If the results in Figure 8 are compared to those in Figure 4 for mean range of alpha particles, the range of the



4000
3000
2000
1000
0
RANGE (CM)
0
2
4
6
8
10
ENERGY (MeV)

FIG. 7



2.0
1.0
0
RANGE (CM)
0
2
4
6
8
10
ENERGY (MeV)

FIG. 8

beta rays is seen to be much greater, as clarified by Example B.

EXAMPLE B: RANGE OF ALPHA AND BETA PARTICLES

Given: The data in Figures 4 and 8.

Find: The difference between the mean range of 3 MeV alpha particles in aluminum and the maximum range of 3 MeV beta particles in aluminum.

Solution: From Figure 4, the mean range of the alpha particles is 0.95×10^{-3} cm.

From Figure 8, the maximum range of the beta particles is 0.55 cm, or almost 600 X the mean range of the alpha particles.

The range of electrons in a material is affected by the number of electrons per unit volume that are present in the material because beta rays give up their energy by collisions with these electrons. The more electrons present in the material, the greater will be the rate of energy loss and the shorter the range. The number of electrons per unit volume is roughly proportional to the density ρ of the material; therefore, an approximate estimate of the maximum range R_m for beta rays of energy E can be obtained from Equation 2.

$$R_m \cong \frac{1}{\rho}(0.54\,E - 0.13) \qquad (2)$$

In this equation, R_m is in cm, ρ in gm/cm^3, and E in MeV. The equation is derived from experiment. Over a reasonable range of energies, it is valid to withing about 15%. The only property of the absorbing material that affects the maximum range R_m is the density ρ.

EXAMPLE C: CALCULATED AND EXPERIMENTAL BETA RANGES

Given: The density of aluminum is 2.7 gm/cm^3.

Find: The difference between the maximum range of beta rays of energy 2 MeV as calculated from Equation 2 and the experimental range from Figure 8.

Solution: Equation 2 gives the following:

$$R_m = \frac{1}{2.7}\ (0.54 \times 2 - 0.13) = 0.352\ \text{cm}$$

Figure 8 gives $R_m \cong 0.36$ cm. The difference in these two values is about 2%.

In order to obtain the maximum range R_m in units of mass per unit area, one must multiply the linear range by the density of the absorber, as in Equation 3.

$$R_m\ (\text{gm/cm}^2) \cong 0.54\ E - 0.13 \qquad (3)$$

R_m is independent, therefore, of the absorbing material and depends only upon the beta-ray energy. This is a reasonable approximation, especially for absorbing materials of low atomic number.

In practice, determination of the maximum range is difficult because the number of beta rays penetrating to the maximum range is very small. If the counting rate for a detector is plotted on a semilogarithmic scale as a function of absorber thickness, a curve such as that shown schematically in Figure 9 is obtained.

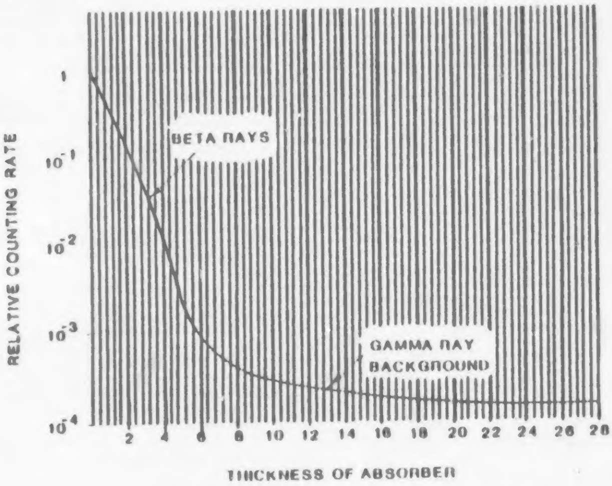


FIG. 9

Near the left part of the Figure 9, the counting rate decreases rapidly with absorber thickness as the beta rays are absorbed. The slower decrease near the right edge is due to the presence of a gamma-ray background. There always will be some gamma rays present. Some radioisotopes emit gamma rays along with beta rays. Even for radioisotopes that emit only beta rays, there will be some gamma rays produced in the absorber itself, as the beta rays interact with electrons. The straight line on the semilogarithmic plot is characteristic of the exponential absorption of the gamma rays (Module 13N4).

The presence of the gamma ray background makes determination of the maximum beta range difficult, since it is difficult to see the point at which the beta ray intensity has dropped to zero in the presence of the interfering background. There are several possible ways to determine the maximum range from experimental data:

- VISUAL INSPECTION. One could try to estimate (from a curve of the type in Figure 9Z where the beta-ray intensity would fall to zero. This method is the least accurate and usually gives estimated ranges that are too small.

- FIT TO A POWER LAW. The beta-ray intensity could be fitted to a power law. One suggested form is Equation 4.

  $$I = K(R_{\ell} - d)^4 \qquad (4)$$

  where
  I = intensity.
  k = constant.
  k_{ℓ} = range in cm.
  d = absorber thickness in cm.

  If the 1/4 power of the intensity is plotted against d, on a linear scale the result should be approximately a straight line. If this straight line is extrapolated to zero, an estimate of the range can be obtained.

- COMPARISON METHOD. The absorption curve is compared to the absorption curve of beta rays from a source whose energy spectrum is known. The comparison method involves a fairly complicated analysis and is beyond the scope of this module. The comparison method does offer a more accurate range determination than the other two methods.

Alpha and beta rays can be detected with a Geiger counter. Because of the relatively short range of alpha and beta rays in solid materials, the Geiger counter must have a very thin window; otherwise, the absorption and energy loss by the window will contribute a signficant error to the measurement. This requirement is particularly true for alpha particles, which have very short ranges, perhaps a few thousandths of a centimeter, in solid materials. Gamma rays, on the other hand, are more penetrating, and the window thickness is less significant.

Geiger counters are available with extremely thin windows. Typically, the window is of a material having a low atomic number — a plastic film or a thin foil of beryllium metal. The manufacturer of the counter will specify the window thickness, in units of gm/cm^2. This thickness must be added to the thickness of the absorbing material in order to obtain the total material thickness.

Another type of counter used for alpha or beta particles is an electrometer. An electrometer has two metal foils, usually made of gold. The foils are hung side-by-side inside a case. A voltage is applied between the walls of the case and the foils. Ionization produced by the alpha or beta particles produces free electrical charge. Charge of one sign is drawn to the case, charge of the other sign to the foils. As the foils become charged, they begin to separate, because like charges repel. The rate of motion of the foils can be used as a measure of the intensity of radiation. The advantage of the electrometer is that no windows are needed. The source is placed inside the electrometer. The disadvantage is that it is less sensitive than the Geiger counter; it is useful only for relatively strong sources.

MEAN RANGE OF ALPHA PARTICLES IN AIR

MATERIALS

Geiger counter, with scaler and high voltage supply. (Counter with thin entrance window is required. An electrometer may be substituted.)
Alpha particle source (Po^{210} or similar source).
Beta particle source (P^{32} or some other pure beta emitter).
Source holder, movable, with screw drive and scale for position measurement.
Mount to hold counter, with center of entrance window at same height as source.
Metal foils (five each):
- Lead: 0.0001" thick.
- Aluminum: 0.0002" thick.
- Aluminum: 0.01" thick.

Holder for metal foils.

PROCEDURE

CAUTION: IN THIS EXPERIMENT, RADIOACTIVE SOURCES ARE USED. THERE ARE POTENTIAL HAZARDS. FOLLOW THE DIRECTIONS OF THE INSTRUCTOR REGARDING USE OF THESE SOURCES.

In these procedures, a Geiger counter with a very thin window may be used. The thickness of the window in units of gm/cm^2 should be known. This value may be specified by the manufacturer of the counter.

Alternatively, an electrometer may be used. This will eliminate corrections due to window thickness. Use of a Brauntype electrometer is preferred. In this electrometer, the moving foil is discharged by a metal stop when it reaches a set displacement. The foil then drops back to its zero position. The foil rises and falls at a regular rate, which may be timed with a stopwatch. The rate of discharge is proportional to the counting rate of a counter.

1. Mount the Po^{210} alpha-particle source on the source holder. Mount the Geiger counter in such a manner that the thin entrance window is pointed toward the source. Adjust the positioning screw for the sample holder so that the sample is almost touching the window. Record position of the scale in Data Table I.
2. Measure counting rate with counter. (Review Module 13N1 for operation of Geiger counter, if necessary.)

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3. Move sample holder away from counter in steps of 2 mm. At each position, measure and record counting rate. Measure and record distance of sample from its original position. Continue measurements until counting rate has dropped to near zero.

4. Plot counting rate versus distance of sample from counter. To each distance, add air equivalent distance of counter window. If thickness of window is specified in gm/cm^2, convert to linear units, using density of air as $0.00129\ gm/cm^2$.

5. From the plot obtained in Step 4, estimate the mean range of Po^{210} alpha particles in air. From Figure 3, estimate energy of alpha particles.

6. Move sample close to the counter, with just enough room to insert metal foils in the foil holder between source and counter. Measure counting rate.

7. Insert aluminum foils one at a time in the sample holder. Measure counting rate after insertion of each foil. Continue until counting rate has dropped to near zero. Use 0.0002" foils for this Step.

8. Plot counting rate versus thickness of aluminum. To the thickness of the aluminum foils, in each case add the equivalent thickness of the counter window. The equivalent thickness is the window thickness in gm/cm^2, multiplied by the density of aluminum ($2.7\ gm/cm^3$).

9. From the plot in Step 8, determine the mean range of the Po^{210} alpha particles in aluminum. Record.

10. Repeat Steps 6, 7, 8 and 9, using lead foils. Determine and record mean range of Po^{210} alpha particles in lead (density of lead is $11.48\ gm/cm^3$).

BETA SOURCE

MATERIALS

Geiger counter, with scaler and high voltage supply. (Counter with thin entrance window is required. An electrometer may be substituted).

Beta particle source (P^{32} or some other pure beta emitter).

Source holder, movable, with screw drive and scale for position measurement.

Mount to hold counter, with center of entrance windown at same height as source.

5-metal foils, aluminum, 0.01" thick.
Holder for metal foils.

PROCEDURE

CAUTION: USE THE SAME PRECAUTIONARY MEASURES AS FOR THE FIRST EXPERIMENT.

1. Mount the P^{32} beta ray source on source holder. Mount Geiger counter in such a manner that the thin entrance window is pointed toward the source. Adjust the distance so that there is barely room for the foil holder between source and counter.

2. Measure counting rate, and record in Data Table 2. Insert foils, one at a time in foil holder; and after each insertion, measure and record counting rate. Use foils 0.01" thick in this Step. Continue until counting rate has reached a low rate, which decreases only slowly as additional absorbers are added.

3. Using semilogarithmic graph paper, plot counting rate versus absorber thickness. For each absorber thickness, add the equivalent thickness of the counter window. Estimate absorber thickness at which beta-ray portion of curve intersects gamma-ray background.

4. On linear graph paper, plot the 1/4 power of the counting rate versus absorber thickness. Near the left edge there should be a portion of the graph that approximates a straight line. Extrapolate this straight line portion back to zero and obtain the maximum range of the beta range in aluminum. Record range. Compare this value to that obtained in Step 3.

5. Using value of maximum range from Step 4, obtain the maximum energy of the P^{32} beta-ray spectrum. Use Equation 2.

DATA TABLE 1: MEAN RANGE OF ALPHA PARTICLES IN AIR

Scale Position	Counting Rate	Steps of 2 mm	Sample Distance from Original Position	Aluminum Foil, 0.002"		Lead Foil, 0.0001"	
				No. of Foils	Range	No. of Foils	Range
				1.		1.	
				2.		2.	
				3.		3.	
				4.		4.	
				5.		5.	

DATA TABLE 2: MAXIMUM RANGE OF BETA RAYS

Scale Position	Aluminum Foils, 0.01"		Maximum Range		Maximum Energy
	No. of Foils	Counting Rate	From Step 3	From Step 4	
	1.				
	2.				
	3.				
	4.				
	5.				

SELF CHECK

1. Define alpha and beta radiation. Include the mass and electrical charge for each.
2. Describe the processes by which alpha and beta particles lose energy in absorbing materials.
3. For alpha particles, define mean range, range straggling, and stopping power.
4. For beta particles, describe the shape of the absorption curve. Define maximum range. State the approximate relation between maximum range and energy.

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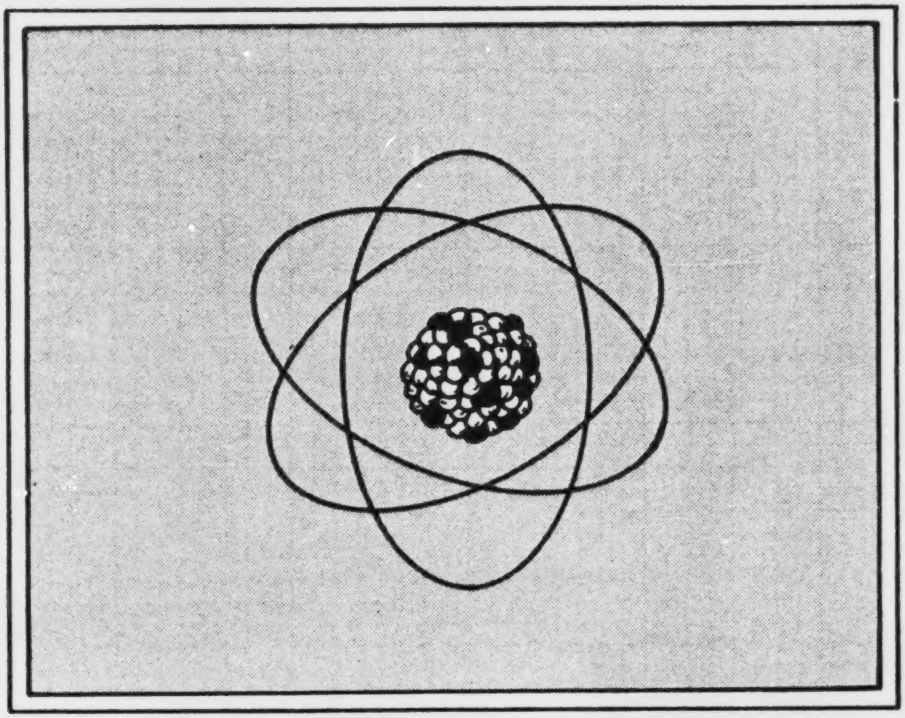
UNIFIED TECHNICAL CONCEPTS

MODULE 13 N 3

RADIOACTIVITY



RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

This module explores radioactivity, the emission of radiation during the decay of the unstable nuclei of atoms. Three different types of radiation are produced, denoted as "alpha," "beta," and "gamma." Radioactive atoms decay over a period of time and are characterized by a "half-life." For different radioisotopes, half-lives vary from a fraction of a second up to billions of years. Radioisotopes have important applications in science, in industry, and in medicine.

In the laboratory, the student will measure the decay rate and source strength of a radioactive source.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Modules 13N4, "Absorption of Gamma Radiation," 13N2, "Penetrative Power of Alpha and Beta Radiation," and 13N1, "Geiger Counters," and have the ability use logarithmic and exponential functions.

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Radioactivity.
  Radioactive series.
  Half-life.
  Curie.

- State the relationship between the parent and daughter atoms for alpha-particle emission and for beta-particle emission.
- Given the necessary information about a radioactive source, calculate its half-life.

- Given the necessary information about radioactive properties of a sample of organic material, determine the sample's age.
- Given the necessary materials and equipment, calibrate a Geiger counter against a standard source and use the result to determine the decay rate, source strength, and number of atoms for a beta-ray emitter.
- Given the necessary materials and equipment, measure the counting rate of a radioactive source as a function of distance from the source, and compare the results to an inverse square law dependence.

DISCUSSION

Radioactivity was discovered accidentally in 1896 by the French physicist Henri Becquerel. Becquerel placed some material containing uranium near photographic plates wrapped in black paper, and later found that the plates had been exposed. He correctly deduced that the uranium was emitting something that could penetrate the paper and expose the photographic plates.

Soon after, Pierre and Marie Curie discovered that ores containing uranium sometimes emit very intense radiation. They used chemical techniques to separate the active elements and, in so doing, identified two new chemical elements, radium and polonium. These two elements are more strongly radioactive than uranium. Madame Curie also correctly showed that the radiation was an atomic phenomenon. Over the next 20 years, studies by E. Rutherford and other workers led to the identification of the nature of the radiation produced by radioactive materials. In addition, many additional radioactive species were discovered. Today, many hundreds of radioactive species are known. Radioactive materials can be produced artificially, and such materials have found practical applications in science, in industry, and in medicine.

Radioactivity is defined as "the production of radiation in the spontaneous dacay of an atomic nucleus." Many types of atomic nuclei, some occurring in nature, are inherently unstable. They decay by themselves, giving off some type of radiation in the process. As a result of the decay, the atomic nucleus changes into a different type of nucleus.

RADIOISOTOPES

Radioactivity is exhibited only by certain isotopes. Recall that atoms with the same atomic number but with different mass numbers, are called "isotopes." For a given chemical element (characterized by a certain atomic number), some isotopes may be radioactive while others are not. Thus, Pb^{210} is a radioactive isotope of lead; Pb^{208} is a stable isotope of lead and does not undergo radioactive decay. The isotopes that undergo radioactive decay are called "radioisotopes."

The early investigators of radioactivity identified three different types of radioactive emission. They arbitrarily named them "alpha," "beta," and "gamma" radiation. They could be separated by electric or magnetic fields. Figure 1 illustrates how a magnetic

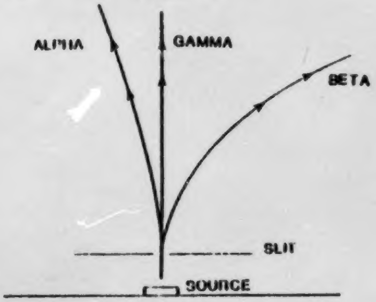


FIG. 1

field (perpendicular to the paper) affects the three types of particles. Alpha rays and beta rays are deflected in opposite directions, with beta rays being deflected more. Gamma rays are unaffected.

Today we know that alpha particles are the nuclei of helium atoms; that beta particles are electrons; and that gamma rays are electromagnetic radiation. The nature of these three types of radiation has been described in Application Modules 13N2 and 13N4. Because the alpha and beta particles have opposite signs of electrical charge, they are deflected in opposite directions by electric and magnetic fields. Uncharged gamma rays are not deflected. For review, the properties of alpha, beta, and gamma radiation are summarized in Table 1.

TABLE 1. PROPERTIES OF ALPHA, BETA, AND GAMMA RADIATION

Type	Nature	Electrical Charge (Units of Electrical Charge)	Mass (gm)
Alpha	Helium nucleus	+2	6.62×10^{-24}
Beta	Electron	-1	9.1×10^{-28}
Gamma	Electromagnetic Radiation	0	0

A particular radioisotope decays in a definite way, either by alpha-particle emission or by beta-particle emission. All the alpha particles from a particular radioisotope have a definite value of energy, usually of the order of a few MeV. The energies of alpha particles from a few selected, naturally-occurring radioisotopes were listed in Module 13N2. Beta particles, however, have a spectrum of energies. The beta particle can have any value of energy, up to a maximum value characteristic of the particular radioisotope. Some values of the maximum energy for the beta rays from some naturally-occurring radioisotopes were given in Module 13N2.

Now we consider the relation of the original nucleus, called the "parent," to the nucleus that remains after the decay, called the "daughter" nucleus. In alpha-particle emission, the emitted particle is a helium nucleus, a stable combination of two protons and two neutrons. Thus, in alpha-particle emission, the atomic number Z decreases by two, and the mass number A decreases by four. This decay is shown schematically in Figure 2.

The figure shows a gamma ray being emitted, in addition to the alpha particle. Alpha-particle emission frequently is accompanied by gamma radiation.

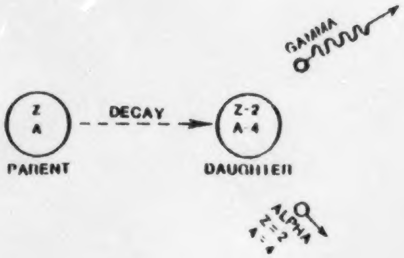


FIG. 2

In beta radiation, the emission is an electron, with one unit of negative charge (Figure 3). The atomic number Z of the nucleus increases by one, because in beta decay, a neutron in the nucleus converts to a proton, thereby increasing the positive charge when leaving the mass number unchanged.

Again, a gamma ray is shown. Usually, beta-particle emission is accompanied by gamma-ray emission. Beta emission always is accompanied by emission of another particle, called the "neutrino." The neutrino has no electrical charge, zero mass, and thus very weak interaction with material. It passes great distances through materials with almost no absorption.

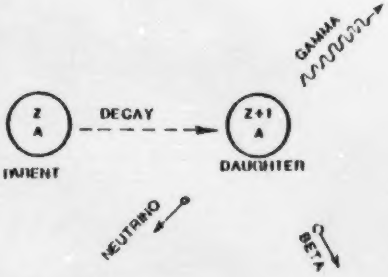


FIG. 3

Often, after a radioactive decay, the daughter neuleus also will be unstable and again undergo radioactive decay. The resulting nucleus again may be unstable. Thus, there can result chains of radioactive decay with a series of radioisotopes. The naturally-occurring radioisotopes at the upper end of the periodic table may be grouped into several different series. Table 2 lists the so-called "uranium series," which begins with U^{238} and ends with a stable isotope, Pb^{206}. The main chain of decay in the uranium series is shown; some of the relatively unimportant branchings of the chain are not shown.

TABLE 2. THE URANIUM SERIES (MAIN CHAIN)

ISOTOPE	ATOMIC NUMBER	RADIATION	HALF-LIFE
U^{238}	92	α	4.5×10^9 years
Th^{234}	90	β	24 days
Pa^{234}	91	β	1.17 min
U^{234}	92	α	2.5×10^5 years
Th^{230}	90	α	7.5×10^4 years
Ra^{226}	88	α	1.62×10^3 years

Rn^{222}	86	α	3.8 days
Po^{218}	84	α	3.05 min
Pb^{214}	82	β	27 min
Bi^{214}	83	β	20 min
Po^{214}	84	α	1.5×10^{-4} s
Pb^{210}	82	β	19.4 years
Bi^{210}	83	β	2.6×10^{6} years
Po^{210}	84	α	138 days
Pb^{206}	82	None	Stable

Inspection of the parent-daughter relationships in the chain is instructive in showing the changes in the nuclei produced by alpha or beta decay. In addition to the uranium series, there is the so-called "thorium series," which begins with Th^{232} and ends with stable Pb^{208}; and, the "actinium series," which begins with U^{235} and ends with stable Pb^{207}.

Most of the naturally-occurring radioisotopes are at the upper end of the periodic table, with atomic number of 83 or more, and are members of one of these series. There are a few naturally-occurring lighter radioisotopes, such as K^{40}. These decay to stable isotopes after only one or two steps and do not give rise to long series.

In addition to the radioactive species that occur in nature, there are hundreds of artificially-produced radioisotopes. The most common method of producing artificial radioisotopes is to bombard stable isotopes with neutrons in a nuclear reactor. A stable isotope (atomic number Z, mass number A) can capture a neutron and be changed to a new isotope with atomic number Z and mass number A + 1. In many cases, the new nucleus with the additional neutron will be unstable and will undergo radioactive decay. Radioisotopes of virtually all the naturally-occurring elements have been produced in this way. In addition, a number of elements with atomic number greater than 92 have been produced by bombardment of atoms with beams of atomic particles. Remember that uranium, with $Z = 93$, has the highest atomic number of any element found in nature. The so-called "transuranium" elements are extremely radioactive. Such elements have been produced with values of Z up to 106.

HALF-LIFE OF ELEMENTS

The half-life for a radioactive element is the time required for half the atoms to undergo radioactive decay. Thus, if we start with N atoms of a particular radioisotope, after one half-life has elapsed, there will be N/2 atoms remaining. After two half-lives, there will be N/4. After 3 half-lives, there will be N/8. Mathematically, the number of atoms remaining is expressed by Equation 1.

$$N(t) = N_o e^{-\ln(\frac{2t}{T_{1/2}})} \qquad (1)$$

where

$N(t)$ = number of atoms remaining after time t.

N_o = number at time zero.

$T_{1/2}$ = the half-life.

We see that when $t = T_{1/2}$, $N(t) = N_o e^{-\ln 2} = N_o/2$, in accordance with the definition of half-life. Equation 1 is employed to solve a problem in Example A.

EXAMPLE A: NUMBER OF ATOMS REMAINING AFTER DECAY

Given: A certain radioisotope has a half-life of 10 days.

Find: The number of atoms remaining (a) after two weeks and (b) after four weeks.

Solution: (a) After 2 weeks, according to Equation 1 —

$$\frac{N\ (14\ \text{days})}{N_o} = e^{-\ln 2 \times 14/10}$$
$$= 0.379$$

Thus, about 37.9% of the original atoms remain undecayed.

(b) After 4 weeks —

$$\frac{N\ (28\ \text{days})}{N_o} = e^{-\ln 2 \times 28/10}$$
$$= 0.144$$

Therefore, 14.4% remain.

Notice that if one chooses the half-life $T_{1/2}$ in days, the time t also must be expressed in days. If $T_{1/2}$ is expressed in weeks, then t would also be expressed in weeks. All that matters is that t and $T_{1/2}$ be expressed in the same units of time.

The rate of decay for radioactive atoms is given by Equation 2.

$$Q\ (t) = \ln 2 \times N\ (t)/T_{1/2} \qquad (2)$$

where

$Q(t)$ = rate of decay at time t; that is, the number of atoms decaying per unit time.

$N(t)$ = number of atoms present at time t.

Thus, as $N(t)$ decreases with time, the decay rate also decreases. The rate of decay for a source can be intense, according to Equation 2, either because the number of atoms is large, or because the half-life is short.

The half-lives of the radioisotopes in the uranium series of naturally-occurring radioisotopes have been listed in Table 2. The values cover a very broad range, varying from a minute fraction of a second up to billions of years. The naturally-occurring series are all headed by a long-lived radioisotope, such as U^{238}, which still remains from the original time of formation of the material of the earth. Other elements with atomic numbers greater than 92 may once have been present, but these elements had shorter half-lives and disappeared long ago. Short-lived isotopes in the uranium series are found in nature because they continually are being replenished by the decay of the isotopes above them in the chain. Thus, Pa^{234} is found in nature, despite its half-life of 1.17 minutes. It is being continually produced by the decay of Th^{234}, which in turn is formed from the decay of U^{238}.

The strength of a radioactive source is measured by the number of atoms that decay per second. The unit of source strength is the curie. A source with strength of 1 curie produces 3.7×10^{10} decays per second.

Equation 2 is clarified in Example B.

EXAMPLE B: DECAY RATE

Given: A source contains 1.5×10^{17} atoms of Ra^{226}.

Find: The activity of the source.

Solution: From Table 2, the half-life is 1.62×10^{3} years, or 5.10×10^{10} seconds. From Equation 2, the decay rate is —

$$(\ln 2)(1.5 \times 10^{17})/5.1 \times 10^{10} = 2.04 \times 10^{6} \text{ decays/s}$$

This value is equal to —

$$2.04 \times 10^{6}/3.7 \times 10^{10} = 5.51 \times 10^{-5} \text{ curies}$$
$$= 55.1 \text{ microcuires}$$

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The number of particles that pass across unit area in unit time from a radioactive source depends upon the distance from the source (assumed to be small, essentially a point) and upon the source strength expressed in numbers of decays per unit time. These quantities affect the intensity of radiation, as indicated by Equation 3.

$$I = \frac{S}{4\pi x^2} \tag{3}$$

where

I = intensity of radiation (particles/cm^2-s).
S = source strength.
π = 3.14.
x = distance from particles to source.

This expression neglects any absorption of the radiation. If the radiation is absorbed by the air, then the value given in Equation 3 will be reduced. The dependence in Equation 3 is commonly called an "inverse square law," because the intensity at a detector is inversely proportional to the square of the distance between the source and the detector. Equation 3 is used to solve a sample problem in Example C.

EXAMPLE 3: RADIATION INTENSITY

Given: A P^{32} beta-ray source of strength 10 microcuries is in a vacuum, so that there is no absorption.

Find: The intensity of the beta radiation at a distance of 15 cm from the source.

Solution: The source emits $10 \times 3.7 \times 10^{10} \times 10^{-6} = 3.7 \times 10^5$ beta rays per second. According to Equation 3, the intensity is as follows:

$$I = \frac{S}{4\pi x^2}$$

$$= \frac{3.7 \times 10^5}{(4\pi)(15^2)}$$

$$I = 131 \text{ beta rays/cm}^2\text{-s}$$

APPLICATIONS

Radioactive isotopes are used in many practical applications in medicine, in science, and in industry. In medicine, radioisotopes are used to test the functioning of certain organs of the body. For example, iodine taken into the body is collected in the thyroid gland. If a small amount of the radioisotope I^{131} is ingested, its location in the body can be followed with a counter. The intake of the I^{131} by the thyroid gland gives a measure of the functioning of the thyroid.

Radioisotopes also are used in medicine as therapeutic agents, often to destroy cancerous tumors. There are many irradiators that use the radioisotope Co^{60}. Gamma rays from Co^{60} are used to irradiate localized cancers, in an attempt to destroy them.

Radioactive decay of C^{14} is used to date biological samples. The isotope C^{14} is maintained in nature at a uniform level by cosmic rays and is distributed throughout the world. Living organisms assimilate the carbon and incorporate it as part of their cells. The activity resulting from the decay of the carbon amounts to 15.3 disintegrations per minute per gram of carbon. When the organism dies, it stops incorporating C^{14}, and the C^{14} that it already has built into its cells gradually decays, with a half-life of 5568 years. If one measures the amount of activity from a biological sample and also determines the total amount of carbon by chemical means, one can obtain an estimate of the age of the sample, as illustrated in Example D.

EXAMPLE D: AGE OF A SAMPLE

Given: Someone shows you a fragment of charred wood that he claims came from the Trojan Horse (10,000 years of age). The weight of the wood is 100 gm. You measure the beta ray activity of the sample and find that it emits 1525 disintegrations per minute.

Find: Age of fragment.

Solution: The charred wood is mostly carbon. If it were 10,000 years old, the original number of C^{14} atoms should have decayed to $e^{-\ln 2 \times 10000/5568}$ or 28.8% of the original value. The original number of decays was 15.3 per gram per minute, or 1530 from the total fragment. The current number of decays should be $0.288 \times 1530 = 441$ decays per minute. But the measured number (1525 decays/min) is much greater. Therefore, you decide that the wood is of much more modern origin.

Radioisotopes are used as heat sources in thermoelectric generators, where radiation is absorbed in the hot junction. The energy absorbed from the radiation keeps the junction hot. Generators powered by heat from radioactive decay have been used as sources of electrical power in remote locations and in the space program.

In industry, radioisotopes are used as gages to measure thickness of a material. The beta-ray source is on one side of the material and a counter on the other side. The counting rate depends upon the material thickness. Such gages can measure thickness of a moving material being produced in a continuous process, without any contact with the material. They are used to measure thickness of coatings applied to thin materials. They have been employed to measure thickness of products such as plastic sheet, paper, thin metal, rubber, and sandpaper. The output of the counter can be employed to control the production process and to ensure the proper thickness of the product.

Radioisotopes are capable of causing harm to human beings. Excessive exposure to radiation from radioisotopes can lead to many health problems, including genetic defects and cancer. Thus, strict safety regulations are applied to the use of radioisotopes; on a national level, the Nuclear Regulatory Commission sets standards for their use. Many states also regulate the employment of radioisotopes. The user of radioisotopes must check the regulations relevant to the intended use and comply with them.

SUMMARY

Radioactivity is "the production of radiation in the spontaneous decay of an atomic nucleus." Isotopes (atoms having the same atomic numbers but different mass numbers) that undergo radioactive decay are termed "radioisotopes." The three types of radioactive emission are alpha, beta, and gamma radiation. Alpha particles (the nuclei of Helium atoms) possess a positive charge; beta particles (electrons) have a negative charge; and gamma rays (protons of high energy) have no charge.

The rate at which radioactive processes take place usually is measured by a quantity called the "half-life" of the material. Although radioactive element loses energy, or "decays," at a rate, the whole period of its life cannot be calculated. Its half-life can be calculated, however, to determine the time required for half its atoms to change.

DECAY RATE AND SOURCE STRENGTH OF K^{40}

MATERIALS

Radioactive sources:
  U^{238} source — chemically purified and of known mass.
  K^{40} source.
Geiger counter, with thin window (<0.02 cm thick aluminum, or equivalent), with scalar and high-voltage power supply.
Aluminum-foil absorbers — 0.05 mm thick.
Holders for sources, counter, and aluminum foils.
Meter stick.
Semilogarithmic graph paper.

PROCEDURE

The student will measure the decay rate and source strength for K^{40}, a beta-particle emitter. The radioisotope K^{40} decays according to —

$$K^{40} \longrightarrow Ca^{40} + \beta + \nu,$$

where β represents the beta particle and ν the neutrino. The isotope Ca^{40} is stable. The maximum energy of the beta spectrum is 1.36 MeV. (This value neglects a relatively small competing mode of decay.)

In order to measure decay rate, one should determine the counting rate of a detector viewing the source and then determine the fraction of the particles counted by the counter (that is, the counter efficiency). The establishment of counter efficiency, unfortunately, is very difficult. In practice, a calibrated source is easier to use to determine detector response, and, hence, to obtain the decay rate of the unknown source.

For the calibration, we will use beta rays from Pa^{234}. The source will be a chemically-purified source of U^{238}. After a U^{238} source is prepared, it is free of atoms of the daughter products. Within a reasonably short time, there also will be decays of Th^{234} and Pa^{234}, by virtue of buildup of these isotopes following alpha decay of U^{238} atoms. (See Table 2.) Because of the relatively long half-life of U^{238}, there will be virtually no decays from radioisotopes lower in the series. Moreover, the beta rays from Th^{234} are very low-energy ones and are removed easily by an aluminum absorber with a thickness of 0.02 cm. Thus, one may have a situation in which the counts from the Geiger counter are dominated by beta rays from Pa^{234}.

If one has two sources, the unknown K^{40} source, and the U^{238} source of known mass, one can calibrate the detector, using the U^{238} source. Then one can use the result to determine the decay rate and the source strength of the unknown source. For the calibration, one uses the known result that Pa^{234} will decay at the rate of 1.22×10^4 beta disintegrations per second for each gram of U^{238} initially present.

1. Mount U^{238} source on sample holder. Mount Geiger counter on its holder, with the thin aluminum window facing toward source. Place source and sample close together, leaving just enough room to insert absorbing foils between them.

2. Measure counting rate from the source (mainly due to Pa^{234} beta particles). Insert aluminum foils one-by-one between source and counter, and measure counting rate after each foil is inserted. Continue until counting rate has dropped to less than 10% of its original value.

3. Plot counting rate versus absorber thickness on semilogarithmic graph paper. Remember to include thickness of counter window in absorber thickness. The curve should be approximately a straight line over a reasonable range of thickness.

4. Extrapolate the straight line portion of the curve back to zero thickness in order to obtain the counting rate at zero thickness. Call this number: $I_o\ (Pa^{234})$.

5. Replace the source with the unknown K^{40} source. Repeat steps 1-4, and obtain a counting rate for zero absorber thickness, $I_o\ (K^{40})$.

6. Determine the counter efficiency η as follows: The total number of disintegrations from Pa^{234} is $1.22 \times 10^4 \times m$ disintegrations per second, where m is the mass of the U^{238} source in grams. The efficiency η is —

$$\eta = I_o \frac{Pa^{238}}{1.22 \times 10^4\ m}$$

7. Obtain the total disintegration rate of K^{40} given by $I_o\ (K^{40})/\eta$. This is expressed in decays per second.

8. Calculate source strength in curies. (Recall, 1 curie = 3.7×10^{10} decays per second.)

9. Calculate number of K^{40} atoms in source. The half-life is 1.6×10^{4} years. Use Equation 2.

COUNTING RATE OF RADIOACTIVE SOURCE

MATERIALS

Same as for first experiment, except that a Co^{60} source is used.

PROCEDURE

The student will verify the inverse square-law dependence of the counting rate on distance from the source. This experiment will use a Co^{60} source. The source emits gamma rays of energy 1.17 and 1.33 MeV, and beta rays with a maximum energy of 0.31 MeV. The beta rays will be removed by an absorber so that all the counts will be due to gamma rays. Since gamma rays of energy greater than 1 MeV have a long range in air, affects due to absorption of the gamma rays in the air will be small. If the experiment were performed using an alpha- or beta-ray source, the dependence could be masked by absorption effects.

1. Mount Co^{60} source in sample holder. Mount Geiger counter on its holder, with the window pointed toward source. Insert aluminum absorbers at least 0.2 mm thick between source and counter to remove beta rays from source.

2. Measure distance x from source to counter with meter stick. Measure counting rate I produced by the gamma rays.

3. Move counter farther from source, and repeat Step 2. Perform measurements at a number of different values of distance, from about 1 cm to 1 meter.

4. Plot the product Ix^2 versus x. The result should be a horizontal straight line, which verifies that the counting rate is decreasing as the inverse square of the distance from the source. (Since $I = S/4\pi x^2$ and S is constant during the measurement, we can write $I = \text{const}/x^2$, or $Ix^2 = \text{const}$. Therefore, if one plots Ix^2 versus x, the result should be a horizontal straight line. Conversely, if the result is a straight line, this means that $I = S/4\pi x^2$, thereby verifying the inverse square law dependence.)

SELF CHECK

1. Define the following terms:

    Radioactivity.
    Naturally-occurring chains of radioactive isotopes.
    Half-life of a radioisotope.
    Curie.

2. State the relationship between atomic number and mass number of the parent and daughter atoms for alpha-particle emission and for beta-particle emission.

3. Three days ago, you had 1.25×10^{19} atoms of a certain radioisotope. Because of radioactive decay, you now have 0.57×10^{18} atoms. What is the half-life of the isotope?

4. While you are digging at an archeological site, you find a fragment of old human bone. By chemical methods, you determine that the bone contains 225 gm of carbon. You measure the beta-ray activity of the material and find that there are 2684 C^{14} decays per minute. How old do you estimate the bone to be?

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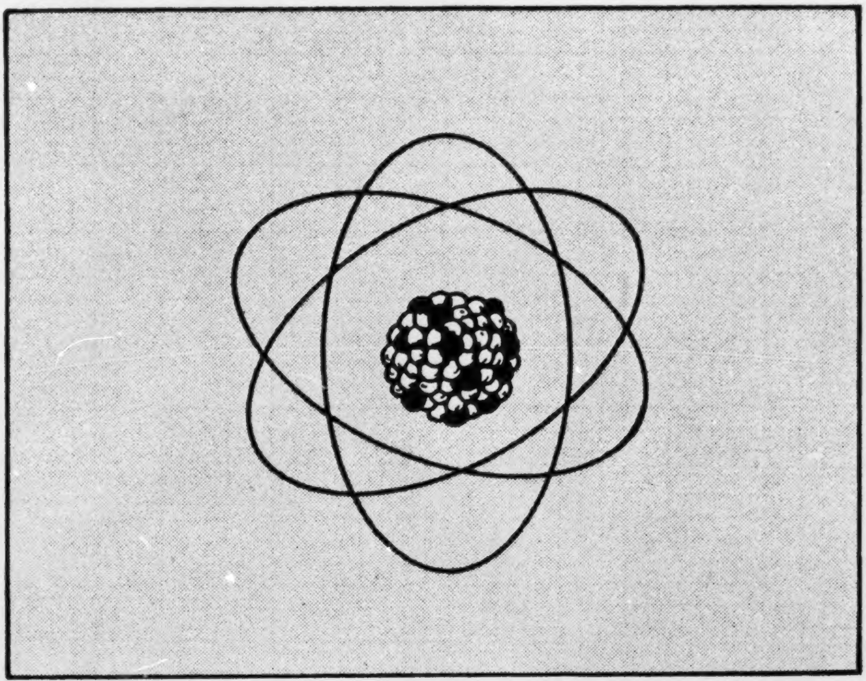
UNIFIED TECHNICAL CONCEPTS

MODULE 13 N 4

ABSORPTION OF GAMMA RADIATION



RADIATION

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Gamma radiation is electromagnetic radiation; that is, the same kind of radiation as light, but of a much shorter wavelength. Gamma radiation is absorbed partially as it passes through a material. This module explains how the absorption follows the same type of exponential equation that describes the absorption of light and is characterized by an absorption coefficient, which depends upon the wavelength of the gamma radiation and upon the nature of the absorbing material.

In the laboratory, the student will measure the transmission of gamma radiation through lead and aluminum, and will use the results to calculate absorption coefficients for these two materials.

PREREQUISITES

Student should have completed Concept Module 13-0, "Radiation," and Application Module 13N1, "Geiger Counters." Student also should have a workable knowledge of exponential functions.

OBJECTIVES

Upon completion of this module, the student should be able to:

- State the relations between energy, wavelength, and frequency for gamma rays; and define ranges of these quantities for gamma rays.
- State the equation for transmission of gamma rays through materials, and define the absorption coefficient.
- State qualitatively how the absorption coefficient varies with gamma ray energy and with the atomic number of the absorber.
- Given the necessary information on material properties, calculate the transmission of gamma rays through the material.
- Given the necessary equipment, measure the transmission of gamma rays through lead and aluminum sheets. Use the results to calculate the absorption coefficients for lead and aluminum.

DISCUSSION

Gamma rays are a form of electromagnetic radiation similar to visible light and radio waves. They share the same wavelike nature. All these different types of radiation travel at the same velocity, the velocity of light, denoted by c and equal to 3×10^{10} cm/s. The nature of electromagnetic radiation has been described more fully in Concept Module 13-0. In this module, the properties of radiation in the gamma-ray portion of the electromagnetic spectrum will be emphasized. Gamma radiation often is denoted as γ-radiation, where γ is a convenient letter in the Greek alphabet corresponding to our letter "g."

Gamma radiation has very short wavelength, much shorter than the wavelength of visible light. Figure 1 gives an expanded view of the short-wavelength portion of the electromagnetic spectrum, and gives the relation between wavelength and frequency for X-rays and gamma rays. For example, a gamma ray of wavelength 10^{-12} cm has a frequency of 3×10^{22} Hz. Figure 1 may be compared to the more complete diagram of the spectrum in Concept Module 13-0.

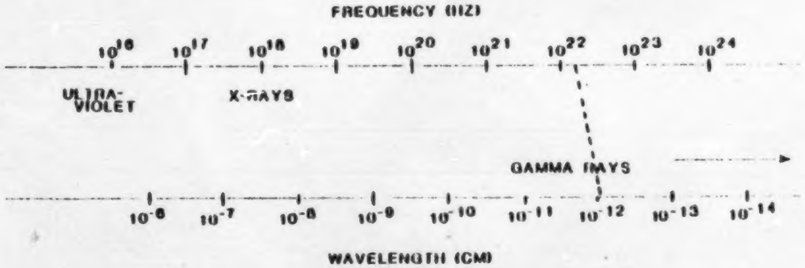


FIG. 1

The wavelength ranges of x-rays and of γ-rays overlap. The boundaries between different regions in the spectrum are not really sharp, definite boundaries but are chosen by convention. The distinction between gamma rays and x-rays arises from the way they are produced. Gamma rays are produced in interactions involving the nuclei of atoms, one common source being the radioactive disintegration of nuclei. X-rays are produced outside the nucleus in the movement of electrons in their orbits; for example, when a high-energy electron collides with an atom and causes a rearrangement of the electrons within the atom, x-rays may be emitted. These two processes both produce radiation in the wavelength range of about 10^{-10} - 10^{-8} cm. There is, therefore, a region of overlap between these two types of electromagnetic radiation.

After an x-ray is produced, it is indistinguishable in form from a gamma ray, except, perhaps, for its energy. The absorption of x-rays will be the same as for gamma rays of the same wavelength.

The wavelength range of gamma radiation extends below 10^{-8} cm. By comparison, visible light is in the wavelength region near 5×10^{-5} cm, thousands of times longer than gamma radiation wavelengths.

The frequency f and wavelength λ are related by the relation given by Equation 1.

$$c = \lambda f \tag{1}$$

where

c = wave speed in meters per second (usually rounded off to 3.0×10^{8} m/s for speed in free space or vacuum).
λ = wavelength in meters.
f = frequency in hertz (cycles per second).

This equation is, of course, the same relation that applies to visible light and the other types of electromagnetic radiation, as well as to wave motion in general. According to this relation, the frequency range for gamma rays extends above 3×10^{18} Hz.

The energy E associated with gamma rays is calculated from Equation 2.

$$E = hf \tag{2}$$

or

$$E = \frac{hc}{\lambda}$$

where

h = Planck's constant = 6.62×10^{-34} J/s.

This relation is valid for all types of electromagnetic radiation. If Equation 2 is used as given, then the energy will be in joules. The energy of gamma rays frequently is expressed in the unit of electron volts. (An electron volt, or eV. is the energy acquired by an electron when it is accelerated through a potential difference ot one volt.) When Equation 2 is recast to yield energy E in electron volts, it takes the form of Equation 3, in which λ is in centimeters.

$$E = \frac{1.245 \times 10^{-4}}{\lambda} \tag{3}$$

If Equation 3 is used with a gamma-ray wavelength of 10^{-8} cm (1A°), gamma-ray energy will be about 1245 eV, which, for convenience, is rounded off to 10,000 eV, or 0.01 MeV (where MeV refers to a million electron volts).

In what has been stated so far, the range of energy or frequency has not been limited on the upper end. In fact, in very high-energy nuclear reactions, gamma rays of extremely high energy (extremely short wavelength) can be produced. A convenient practice is to express a boundary limited by the energies available in radioactive decay of nuclei, about 4 MeV. This value corresponds roughly to a lower-wavelength limit of 3×10^{-11} cm and to an upper frequency limit of 10^{21} Hz. The ranges are summarized in Table 1.

For all nuclear processes, there is no defined limit. In fact, gamma rays with wavelength shorter than 10^{-25} cm have been detected in cosmic rays coming from outside the solar system. But for gamma rays originating in radioactive decay, there is a lower limit to the wavelength, as indicated in Table 1.

TABLE 1: APPROXIMATE RANGES FOR GAMMA RAYS

	All nuclear processes	Radioactive decay
Energy	>0.01 MeV	0.01 - 4 MeV
Wavelength	$<10^{-8}$ cm	$3 \times 10^{-11} - 10^{-8}$ cm
Frequency	$>3 \times 10^{18}$ Hz	$3 \times 10^{18} - 10^{21}$ Hz

As examples of isotopes that undergo radioactive decay and produce gamma rays, Table 2 lists the energies of gamma rays emitted by several selected isotopes of various elements. Some radioactive isotopes can emit gamma rays of more than one energy. Following Table 2, Example A illustrates a typical calculation of wavelength and frequency corresponding to a gamma ray of given energy.

TABLE 2: GAMMA RAYS EMITTED BY SELECTED RADIOACTIVE ISOTOPES

Isotope	Gamma ray energy (MeV)
Be^7	0.48
Na^{24}	1.37 and 2.75
Cr^{51}	0.32
Co^{60}	1.17 and 1.33
Cs^{137}	0.66

Au^{298}	0.41
$T\ell^{208}$	0.51, 0.58, 2.61
Am^{241}	0.026 and 0.060

EXAMPLE A: CALCULATION OF WAVELENGTH AND FREQUENCY

Given: The isotope Bi^{214} emits γ-rays of energy 0.77 MeV.

Find: The corresponding wavelength and frequency.

Solution: Use Equation 3:

$$\lambda = \frac{1.245 \times 10^{-4}}{}$$

$$= \frac{1.245 \times 10^{-4}}{700{,}000}$$

$$\lambda = 1.62 \times 10^{-10} \text{ cm}$$

Use Equation 1 (rearranged for f):

$$f = \frac{c}{\lambda}$$

$$= \frac{3 \times 10^{10}}{1.62 \times 10^{-10}}$$

$$f = 1.85 \times 10^{20} \text{ Hz}$$

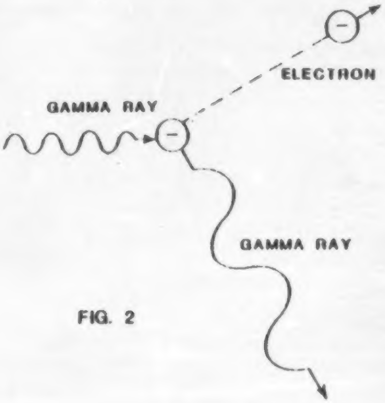


FIG. 2

As gamma rays travel through any material, they interact with the electrons and atoms in the material. A variety of physical processes such as scattering can occur. The gamma ray interacts with an electron and transfers some of its energy to the electron. Then a gamma ray of lower energy, or of longer wavelength, emerges. Also, an electron emerges, with kinetic energy equal to the energy given up by the gamma ray. The process, known as "Compton scattering," is shown schematically in Figure 2. The electron is denoted with a minus sign, to indicate its negative electrical charge. The electron emerges in one direction and the gamma ray, with longer wavelength, in a different direction. Notice that the final gamma ray has its direction changed from its initial direction of travel.

Another process involves transfer of all the energy of the gamma ray to an electron. This process is called "photoelectric absorption." In this case, the electron is in orbit around the nucleus of an atom and is transferred to a different orbit, an orbit with greater energy than the initial one, or is removed entirely from the atom. The gamma ray disappears. Figure 3 shows this process schematically, with the electron and the nucleus denoted by minus and plus signs, respectively, to show their electrical charge.

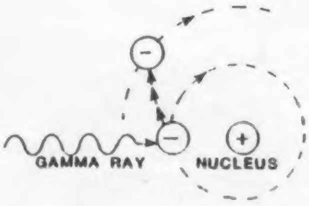


FIG. 3

Because electrons in atoms have discrete energies in their different orbits, the absorption spectrum for gamma rays shows sharp peaks where the gamma ray energy equals the difference in energy between different electronic orbits. The absorption of the gamma rays plotted versus gamma-ray energy, thus appears as shown in Figure 4. The sharp, discontinuous increases in absorption with increases in energy are called "absorption edges." At an absorption edge, the gamma-ray energy equals the energy difference between two electronic orbits in the atom. The positions of the absorption edges depend upon the absorbing atom. Thus, the presence of a particular type of atom can be determined by the occurrence of its characteristic absorption edges in a gamma-ray spectrum. As a result, gamma-ray absorption can be used for chemical analysis.

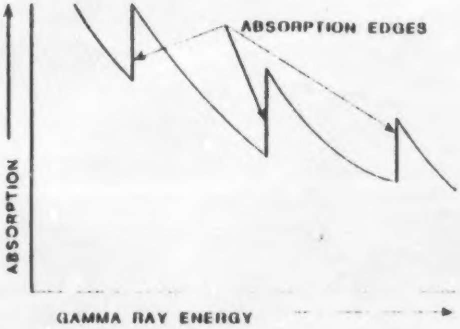


FIG. 4

There are also other physical processes by which gamma rays lose energy; however, this discussion will be restricted to the scattering and photoelectric absorption phenomena discussed above.

Because of these processes, the intensity of gamma radiation decreases as it passes through a material. The intensity can be expressed by an exponential equation (Equation 4).

$$I_x = I_o e^{-\mu x} \qquad (4)$$

where

I_x = intensity of gamma rays after passing through distance x of material.
I_o = initial intensity.
μ = a parameter, called the "absorption coefficient." having dimensions of reciprocal length (for example, cm^{-1}).

Figure 5 gives the transmission, defined as I_x/I_o, as a function of absorber thickness, when the absorption coefficient is 1 cm^{-1}. The figure shows the characteristic shape of the exponential absorption curve, as defined by Equation 4.

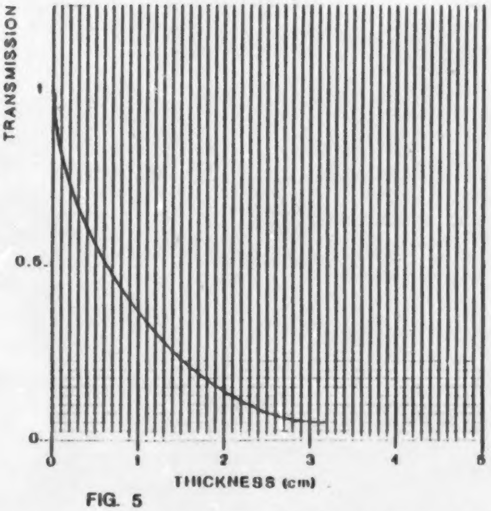


FIG. 5

The exponential absorption, as given by Equation 4, is exactly the same as that for the absorption of light as it travels through an absorbing material.

If the logarithm of each side of Equation 4 is taken, Equation 5 is the result.

$$\ln\left[\frac{I_x}{I_o}\right] = -\mu x \qquad (5)$$

or

$$\mu = -\frac{1}{x}\ln\left[\frac{I_x}{I_o}\right] = \frac{1}{x}\ln T \qquad (6)$$

where

T = transmission.

Thus, the absorption coefficient μ can be defined as "the fractional decrease in gamma-ray intensity per unit length of the absorbing material." Example B illustrates a typical problem involving the transmission of gamma rays through aluminum.

EXAMPLE B: TRANSMISSION OF GAMMA RAYS

Given: For an aluminum absorber irradiated by gamma rays of energy 1 MeV, the gamma-ray absorption coefficient is 0.162 cm^{-1}.

Find: The transmission I_x/I_o, which is the fraction of the incident gamma rays transmitted through a 10-cm thickness of aluminum.

Solution: According to Equation 4, the fraction transmitted through thickness x is as follows:

$$\frac{I_x}{I_o} = e^{-\mu x}$$

Substituting $\mu = 0.162\ cm^{-1}$ and x = 10 cm gives —

$$\frac{I_x}{I_o} = e^{-0.162 \times 10}$$

$$= e^{-1.62}$$

$$\frac{I_x}{I_o} = 0.198$$

Thus, 19.8% of the incident gamma rays are transmitted.

The absorption coefficient is a complicated function of gamma-ray energy and properties of the absorber. Several different processes (photoelectric absorption, scattering, etc.) contribute to the value of the absorption coefficient. Each process has its own particular contribution; therefore, one cannot state simply how the absorption coefficient varies. One can relate, however, the density of the absorber, the atomic number of the absorber, and the gamma-ray energy to the absorption coefficient. This relationship is explained in the discussion that follows.

ABSORBER DENSITY

Since gamma rays are absorbed by interactions with electrons in the absorber, the absorption coefficient increases with the number of electrons per unit volume in the absorber. The electrons per unit volume are roughly proportional to the density of the material; consequently, a useful quantity is μ/ρ, the absorption coefficient divided by the density ρ of the absorber. This combination is called the "mass absorption coefficient" and is derived from Equation 7.

$$\mu_m = \frac{\mu}{\rho} \tag{7}$$

where

μ_m = mass absorption coefficient in units of cm^2/gm.

ρ = density of absorber.

The mass absorption coefficient is the fraction of gamma-ray energy absorbed from a beam of unit area by one gram of absorbing material. In the literature on gamma rays, the mass absorption coefficient often is used. The student must be careful to distinguish between the quantities μ and μ_m.

If Equation 7 is used in terms of the mass absorption coefficient μ_m, the basic absorption equation becomes the form expressed by Equation 8.

$$I_x = I_o \, e^{-\mu_m \rho x} \qquad (8)$$

The form of Equation 8 allows the thickness of the absorbing material to be expressed by the quantity ρx, which has units of gm/cm^2. Frequently, in work involving shielding, radiation protection, and radiation absorption, the thickness of the absorbing material will be expressed in these units. In this case, the thickness is to be interpreted as the product of the density ρ and the physical thickness x. Example C illustrates a typical calculation involving the concept of absorber thickness.

EXAMPLE C: CALCULATION OF ABSORBER THICKNESS

Given: For an aluminum absorber and gamma rays of energy 1 MeV, the mass absorption coefficient is given as 0.06 cm^2/gm.

Find: The thickness, if 10% of the gamma rays penetrate the absorber.

Solution: According to Equation 8, the fraction transmitted through thickness ρx gm/cm^2 is –

$$\frac{I_x}{I_o} = e^{-\mu_m \rho x}$$

or,

$$0.1 = e^{-0.06\, \rho x}$$

Taking logarithms gives –

$$-2.30 = -0.06\, \rho x$$

or the thickness ρx is –

$$\rho x = 38.4 \text{ gm/cm}^2$$

Since aluminum has a density of 2.7 gm/cm^2, this value corresponds to a physical thickness of –

$$x = \frac{38.4}{2.7}$$

$$x = 14.2 \text{ cm}$$

ATOMIC NUMBER OF ABSORBER

The atomic number Z of the absorber plays an important role in determining the value of the absorption coefficient. In general, the absorption coefficient increases with an increasing atomic number. Thus, materials of high atomic number, like lead, are more efficient absorbers of gamma rays than are materials of low atomic number, like aluminum. Therefore, materials like lead are used as shielding materials for radiation protection.

This increase in absorption efficiency with an increasing atomic number is greater than the increase in density. The amount of the increase depends upon the energy regime. For some values of gamma-ray energy, the mass absorption coefficient increases approximately as the fourth power of Z. The mass absorption coefficient, therefore, could be much greater for a given thickness of an absorber of high Z than for the same thickness of an absorber with low Z.

The mass absorption coefficients for lead and for aluminum are shown graphically in Figure 6 as functions of energy. The ratio of μ_m between the two materials changes at different energy ranges. For relatively low energies ($\lesssim$ 0.1 MeV) and relatively high energies ($\gtrsim$ 10 MeV) the mass absorption coefficient of lead is much higher than that of aluminum. In the range around 1 MeV, the mass absorption coefficient for lead is only slightly higher than for aluminum. Also, in the energy range shown in Figure 6, we notice that lead has two absorption edges, whereas aluminum has none. Energy dependence is explained next.

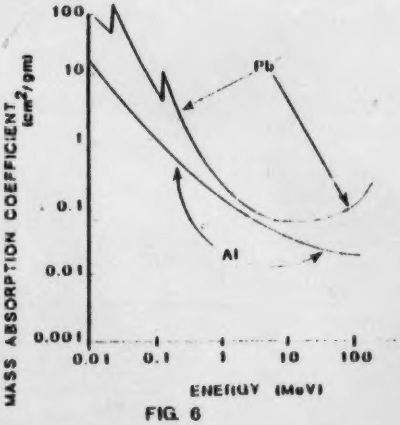


FIG. 6

GAMMA-RAY ENERGY

The mass absorption coefficient is a complicated function of gamma-ray energy, as already demonstrated in Figure 6. Since various physical processes contribute to the absorption of gamma rays, different processes contribute differently to the absorption of gamma rays at different energies.

In general, the behavior of a given absorber is as shown in Figure 6. As energy increases over the range 0.01 - 1 MeV, the mass absorption coefficient generally decreases, although it may pass through several discontinuous jumps at absorption edges. The total decrease can be very large, greater than a factor of 1000, as the figure shows. The mass absorption coefficient usually exhibits a minimum in the region between 1-10 MeV, with the exact position depending upon the nature of the absorber. Then as energy increases further, the mass absorption coefficient again increases.

EXAMPLE D: SHIELDING

Given: Gamma rays are incident upon lead absorbers. Lead has a density of about 11.5 gm/cm^3.

Find: Thickness of lead that will decrease the intensity of a beam of gamma rays to 1% of its original intensity if the gamma-ray energy is (a) 0.1 MeV; and if it is (b) 3.5 MeV.

Solution: (a) For 0.1 MeV, the mass absorption coefficient is about 5 cm^2/gm. Use of Equation 8 gives the following:

$$0.01 = \exp\ (-5\ \rho x)$$

Taking logarithms of each side yields this value:

$$-4.61 = -5\ \rho x$$

or

$$\rho x = 0.92\ gm/cm^2$$ (physical thickness is 0.08 cm)

(b) For 3.5 MeV, $\mu_m \simeq 0.04\ cm^3/gm$, so that

$$0.01 = \exp\ (-0.04\ \rho x)$$

or

$$-4.61 = -0.04\ \rho x$$

or

$$\rho x = 115\ gm/cm^2$$ (physical thickness is 10 cm)

Thus, a much greater thickness is required to reduce the intensity of 3.5 MeV gamma rays to 1% of the original value.

SHIELDING

The level of radiation reaching personnel from a radiation source is reduced by shielding; that is, by absorbing materials placed between the personnel and the source. The shielding material must be of sufficient thickness to reduce the radiation to a level consistent with radiation protection standards.

For shielding from gamma radiation, one should use shields of lead or of other materials having high atomic numbers. Knowing the value of the absorption coefficient for the gamma-ray energy of interest, one can use Equation 4 to calculate how thick the absorber must be to reduce the radiation to the desired level. According to Equation 4, no amount of shielding will reduce the intensity of gamma radiation to zero.

SUMMARY

Gamma radiation is electromagnetic radiation; that is, the same kind of radiation as light, but of a much shorter wavelength. Gamma radiation is absorbed partially as it passes through a material. The absorption follows the same type of exponential equation that describes the absorption of light and is characterized by an absorption coefficient, which depends upon the wavelength of the gamma radiation and upon the nature of the absorbing material. Gamma rays are emitted by the nuclei of radioactive atoms during decay. Such rays are very penetrating and may be harmful to the human body.

TRANSMISSION OF GAMMA RADIATION THROUGH MATERIALS

MATERIALS

Geiger counter — end-window type, with stand, scaler, and high-voltage power supply.
Radioactive gamma-ray source (for example Co^{60}).
Source holder.
Lead sheets (about 10, each 3mm thick).
Aluminum sheets (about 10, each 1 cm thick).
Semilogarithmic graph paper.

PROCEDURE

In this experiment, the student will measure the transmission of gamma rays through absorbers of lead and of aluminum. The results will be used to determine the value of the absorption coefficient for each of these materials.

CAUTION — Excessive exposure to radiation from radioactive sources can be seriously harmful. Consult with your instructor for necessary precautions before handling the radioactive source.

1. Set up Geiger counter and scaler, and turn them on. Mount counter on a stand. Mount the sample of radioactive material in a tray on the stand, and orient it in such a manner that the counter end window is pointed toward it. Move sample either nearer or farther from the counter (change trays) until the counting rate is at a reasonable level on a high scale.

2. Measure the counting rate (counts per minute obtained over two-minute intervals) with no absorbers between the source and counter. Record rate here: ________________. Next, insert lead sheets one at a time between the source and counter. After each sheet is inserted, remeasure the counting rate (over two-minute intervals) and record here: ____________. Continue until the counting rate has been reduced to less than 10% of its original value. Change scales on the scaler if necessary to obtain accurate values at the lower counting rates.

3. Plot the counting rate (cpm) as a function of absorber thickness (cm), on semilogarithmic graph paper. (Plot cpm along the y-axis; absorber thickness along the x-axis.)

4. Draw the best straight line through the points. Choose two points on the straight line such that the counting rate differs by a factor of 2. The corresponding difference in absorber thickness related to these two points gives $x_{1/2}$, the thickness needed to reduce the intensity to 1/2 of its value. Determine $x_{1/2}$ directly from the graph. Then determine the absorption coefficient μ from the following equation: $\mu = 0.693/x_{1/2}$, or _______________. Next determine the mass absorption coefficient $\mu_m = \mu/\rho$. (The density ρ of lead is 11.48 gm/cm^3.) _____________.

5. Repeat steps 2, 3, and 4 using aluminum sheets instead of lead. (The density of aluminum is 2.7 gm/cm^3.)

SELF CHECK

1. State the relationships between energy, wavelength, and frequency for gamma rays. Give reasonable ranges of energy, wavelength, and frequency for the gamma-ray portion of the electromagnetic spectrum.

2. State the equation that controls the transmission of gamma rays through materials. Define absorption coefficient.

3. State qualitatively how absorption coefficient varies with gamma-ray energy and with the atomic number of the absorber.

4. How is the mass absorption coefficient related to the absorption coefficient?

5. For gamma rays of energy 0.055 MeV, the mass absorption coefficient of water is 0.2 cm^2/gm. The density of water is 1 gm/cm^3. What fraction of gamma rays of this energy will penetrate through 1 cm of water? Through 10 cm?

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